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AN AID FOR THE OPTIMUM DESIGN OF ANTENNA
SYSTEMS FOR VERY LOW FREQUENCIES

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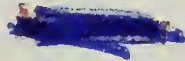
AN AID FOR THE
OPTIMUM DESIGN OF ANTENNA SYSTEMS
FOR VERY LOW FREQUENCIES

by

James Thomas Gobbel, Jr.

Lieutenant, United States Navy

B.S.E.E., Duke University, 1962



Submitted in partial fulfillment of the
requirements for the degree of
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ABSTRACT

This thesis will be concerned with the antenna systems used for high power radio transmitters operating at Very Low Frequencies (10-30 kHz). General problems involved in antenna systems, from the viewpoint of their equivalent electrical circuits, will be discussed. The required matching networks will be covered and their relative performances indicated. A brief survey of signalling methods commonly used at VLF is included, and the relation between these methods and the aerial systems is discussed.

A computer program (VLFANT) will be developed for a typical VLF aerial installation which may be used in the selection of component values for optimum operation. Written in FORTRAN IV, it is for use on a high-speed digital computer. Circuit parameter values may be changed at will, and the system response using different network arrangements easily determined. With this program as a design tool proposed systems may be completely evaluated and the proposed changes to operational systems easily studied.

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I. INTRODUCTION

This thesis will be concerned with the design of antenna systems used for radio communications at Very Low Frequencies (10-30 kHz). Principles of design and operation of the systems, from the viewpoint of their equivalent electrical circuits, will be discussed. The design and use of matching systems will be covered, and a brief analysis of information transmission methods used at VLF will be included.

Selection of the proper complete antenna system is difficult, and under field conditions the best designed system may not function efficiently. In order to choose component values for optimum operation, a computer program (VLFANT) will be developed. Parameter values may be varied at will and their effect on overall operation quickly determined.

The computer program is written in FORTRAN IV language for use on a high-speed digital computer such as the IBM System/360. The U. S. Navy VLF installation at Northwest Cape, Australia has been selected as a model and its performance will be discussed. Modification for other installations may be easily accomplished.

Historically, the Very Low Frequency spectrum was used as the primary long range communication medium, with a number of stations being built in the period from 1910 to 1912 for world-wide service.^{1*} Beginning in the 1920's, however, with the discovery and subsequent high usage of the "shortwave" frequencies, the utilization of the 10-30 kHz range for long distance communications rapidly declined. But within the last decade VLF has again come into wide use by both the civilian and

* Numbers in superscript refer to references, listed at the end of this thesis.

military communities for accurate time and frequency standards, navigation and specialized communications. This renewed interest is due to the predictable propagation characteristics of these very low frequencies, the long ranges attainable, and the ability to penetrate the ocean depths, a requirement raised by man's new interest in the under-sea world.² As of July, 1963 over 90 VLF transmitters were known to be operating below 30 kHz and in the past few years others have been added.¹ The lowest operating frequency regularly in use is 10.2 kHz, which is part of the U. S. Navy Omega navigation system, while the lowest frequency used for communications is 15.5 kHz at the U. S. Navy VLF station at Northwest Cape, Australia.³

The earth and lower edge of the ionosphere tend to act as concentric shells which guide VLF radio waves. There is little penetration into the ionosphere by the skywave portion of the signals and very small attenuation of the groundwave. Thus signals of notable strength may be produced at distances of up to 1,000 km. Absorption and attenuation tend to decrease in winter, at night, and with decrease in frequency. The major loss in signal strength is a function of distance from the transmitter; fading is never observed.⁴ Solar activity can cause a change in VLF propagation, but the lower the frequency the less the effect. For the same reason VLF is relatively immune to nuclear blackout.⁵

Despite these advantages VLF is not completely utilized because the aerial systems are large and inefficient, with much of the generated radio frequency power going into ground and copper losses. Additionally, the total number of stations which can operate is limited and each station is therefore restricted to a narrow modulation band.⁶

A typical modern VLF communications transmitting installation uses very high power, often in the hundreds of kilowatts. The antenna is very large physically, and the associated components must have good mechanical strength and be able to withstand high voltage and current gradients.⁵ In fact, the rf feed-through bushings for Northwest Cape are about 16 feet tall and weigh almost 3.5 tons apiece.

With such an investment in materials, cut and try methods of design cannot be used. A proposed system must be painstakingly detailed, and such variables as stray capacitance included in the theoretical analysis. In the past, prior experience with operating installations has been combined with modelling studies in an attempt to get the best design. Exact mathematical descriptions of operations may have been available, but the evaluation of the expressions could take months to complete, and with a slight change in a single parameter could have been rendered useless. Also the form of a system might not fit the nice geometric configurations of a model, calling for approximation techniques whose accuracy would be "ball park" at best.

Today this hurdle is being overcome with the use of high-speed digital computers. Commercial antenna manufacturers are designing their systems with the aid of computer programs, still retaining models, however, as a check on the theoretical results. As one antenna engineer has said:

It is significant that the properties of an antenna configuration, for example, can be evaluated more economically by computer techniques than by experimental methods; however, it is perhaps even more important that the computer can also be programmed to change the antenna configuration in a systematic way to find a structure that is optimum in certain respects. It is not at all unrealistic to expect that an optimization that might take several weeks if done 7 experimentally can be done within ten minutes by computer.

This thesis, then, will be concerned with one part of a VLF transmitting facility: the interconnection of a previously designed VLF antenna with the transmitter. A review of basic principles of such a connection will be presented first, and then a computer program developed to aid in the optimum selection of the coupling network.

II. BASIC PRINCIPLES

This section will discuss some of the basic principles applicable not only to the design of the VLF aerial itself but to the matching networks and signalling methods which must be considered in the design of the overall antenna system.

A. Aerials

It has been stated many times that the most important part of a transmitter installation is the antenna system, since the best transmitter is practically worthless if its energy cannot be properly matched to the atmosphere and radiated into space. This is especially true in the Very Low Frequency range.

Wavelengths range from 10 km (16 statute miles) at 30 kHz to 30 km (48 statute miles) at 10 kHz. The simple half-wave dipole which is so popular in the High Frequency bands might be possible here if the required real estate was available. But for long range propagation of VLF signals, vertical polarization is necessary, and the quarter-wave vertical antenna would have to be 7.5 km (12 statute miles) high. Consideration of supports and protection against the elements clearly makes such an installation impossible.

Since VLF signals are generally "broadcast" in an omnidirectional pattern, some form of single vertical radiator seems the most appropriate aerial to use. Towers are generally limited to about 1,000 feet (305 meters), although there are cases where geographical features may be utilized to increase the height.⁸ With a limit to the physical height of the aerial, it is proper to consider possible increases to the electrical height.

Consider a transmission line which is one-quarter wavelength long electrically, fed with a sinusoidal input, and terminated in a resistive load much greater than its characteristic impedance. The current through the load will be very small, the voltage across the load high. As we move from the load towards the generator the current will increase while the voltage will decrease, and a phase difference will develop between the two. At the generator end of the line the voltage and current will be in phase again. If the impedance at any point along the line is defined to be the quotient of the voltage divided by the current, then we see that due to the difference in phase, the impedance will have a magnitude and a phase. With current leading the voltage the impedance phase will be negative, the same condition as exists for a simple circuit composed of a resistor and capacitor.

The vertical aerial may be compared to a transmission line, and since it is less than a quarter wavelength long, it, too, will exhibit a capacitive reactance at the "generator" terminals. If some additional capacitance was added at the top of the aerial it would appear electrically to be just more "transmission line" and thus appear longer electrically. The 1,000 foot tower is so very much shorter than a quarter wavelength that in general the more capacitance we can add the longer the aerial will appear. This addition of capacitance is known as "top loading" and the capacitor itself is known as the "top hat" due to its physical arrangement.

Actual construction often consists of a number of horizontal wires run radially from the central tower to outlying towers, for distances up to 8,000 feet, forming a circular electrical "plate," covering up to two square miles. The other "plate" for the capacitor

is the ground, which must be more than just the earth. The basic operation of a quarter-wave vertical aerial depends on an "image" aerial of equal length to be formed in the "ground," so the earth ground system must form a "ground plane."

As might be assumed from the discussion above, the proper design of a VLF aerial system is relatively complex. Although the use of modern analysis has been suggested, it has been the practice up to this time to apply basic and empirical formulae and then make a model of the proposed system.^{7,9,10}

An example of such an approach is the design of the aerial for the U. S. Navy station at Cutler, Maine. First, a number of designs were studied in theory and many rejected; the most promising were then modeled using a scale of 2500:1.¹¹ The best of these models were then selected and new models were made with a scale of 100:1.¹² A final report was then issued with a recommended antenna, including extensive cost data, preliminary sketches, computational results, modelling results, and predicted performance against the elements, including high winds and ice loading.¹³

Two important parameters for the resulting aerial system are the radiation resistance and the effective height, which is "the height of the antenna center of radiation above the effective ground level."⁹ The latter is usually determined from modelling measurements. The radiation resistance is the true "load" of the aerial and power dissipated in this "load" is actually radiated into space. These two parameters are proportionally related through a simple expression. The radiation resistance normally has a magnitude on the order of one ohm.

Figure 1 shows a sketch of the aerial system in use at the VLF station at Northwest Cape, Australia.

Once the final aerial system design has been made, it is possible to consider the system as a series electrical circuit, such as shown in Figure 2. The radiation resistance is the "load," ohmic resistances of the tower and cables are lumped into the loss resistance term, the capacitance is primarily that of the top-hat, and the downlead to the transmitter forms the inductance.

A more thorough analysis would show other reactive elements such as stray capacitance, but they have been combined where possible and ignored when practical. It is also possible to use more than one downlead but that will not be considered here.⁵

In standard network analysis the reactances would be combined and the sum considered as a single parameter. This will be done later when it comes to impedance matching, but for the aerial itself the reactances must be considered separately. For a typical VLF aerial the capacitive reactance can be assumed to be about four times greater in magnitude than the downlead reactance.

The static capacitance (neglecting the downlead inductance) determines the major limits for a VLF aerial. The "Q" or quality factor is defined to be the ratio between the stored and dissipated energy, or the capacitive reactance divided by the radiation resistance. The Q also determines the aerial circuit bandwidth. For VLF aeri-als the Q has a value of several hundred, and the bandwidth is measured in ten's of Hertz.

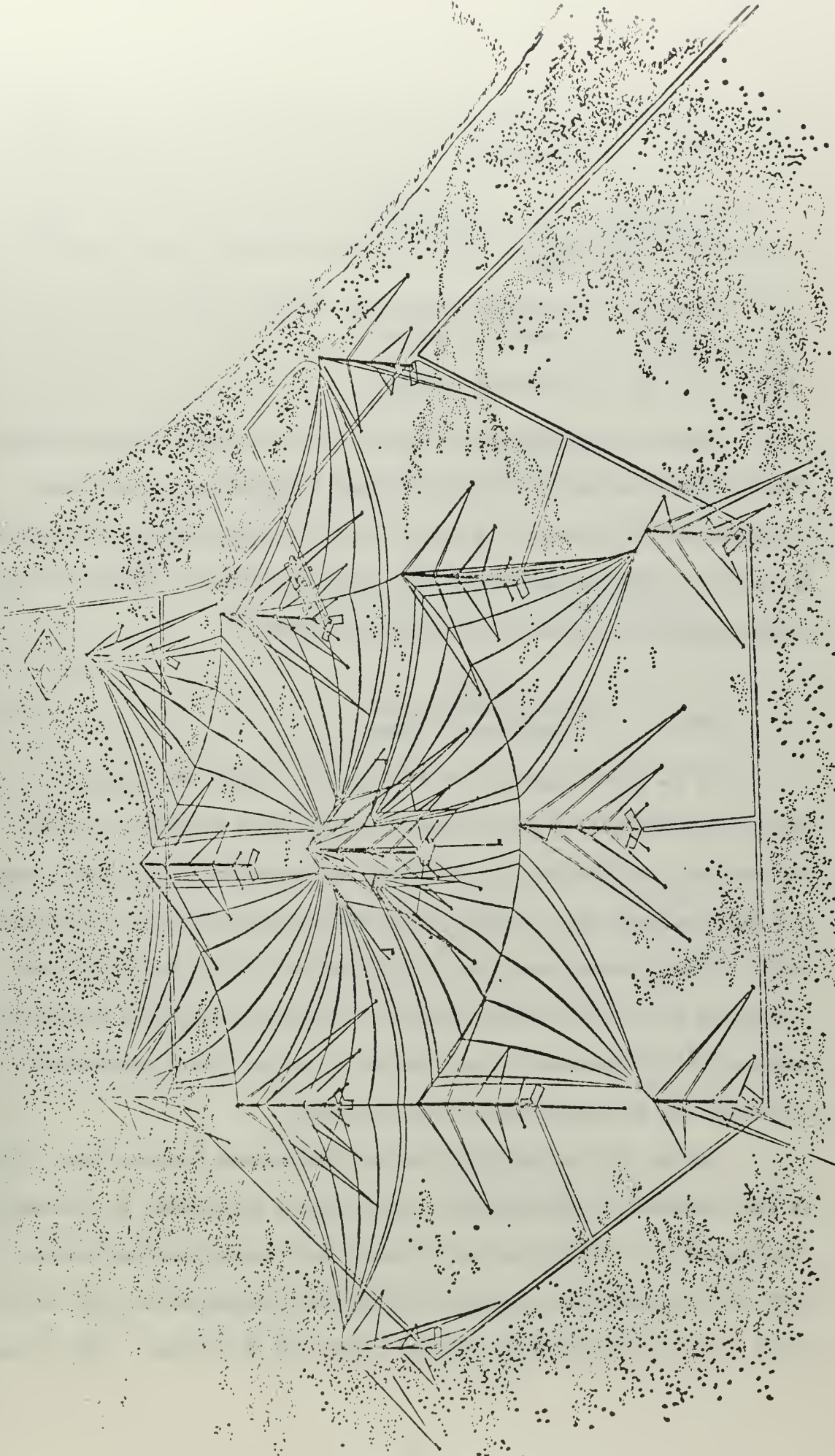


Figure 1.
Aerial Structure - Northwest Cape, Australia

$$Q_{\text{ant}} = \frac{|jX_c|}{R_{\text{radiation}}} \quad \dots(1)$$

$$\text{Bandwidth} = \frac{f_o}{Q_{\text{ant}}} \quad \dots(2)$$

where X_c = capacitive reactance at the operating frequency

f_o = operating frequency

There is a second set of values for the aerial Q and bandwidth often encountered which involves the loss resistance. At the input terminals of the circuit in Figure 2 the loss and radiation resistances are seen as a single resistance sum. From the network analysis viewpoint, Equation (1) must be modified as follows:

$$Q_{\text{ant}} = \frac{|jX_c|}{R_{\text{radiation}} + R_{\text{loss}}} \quad \dots(1.a)$$

If an aerial system with the loss and radiation resistances equal is considered, the Q as seen from the input terminals is only one half that of the aerial itself and the bandwidth is doubled. Since the losses depend upon the actual aerial installation and the associated coils, leads, ground, etc., the Q in Equation (1) is the one of most concern in the initial aerial design. From the operational viewpoint, however, the Q determined from Equation (1.a) and the corresponding bandwidth are the parameters of most concern.

One of the two major VLF system limitations appears here. This is the breakdown voltage rating of the various components in the aerial. (The second is a limitation on the power the transmitter can produce.) With the low radiation resistance, high power necessitates high current which in turn produces high voltage across the reactances. The voltages

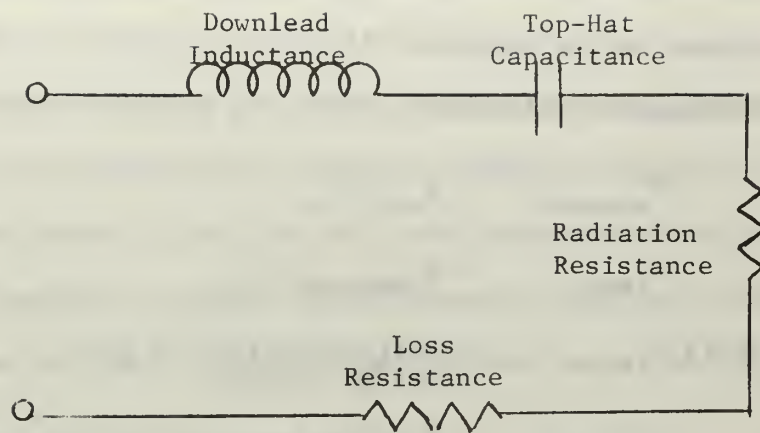


Figure 2. Basic Aerial Circuit

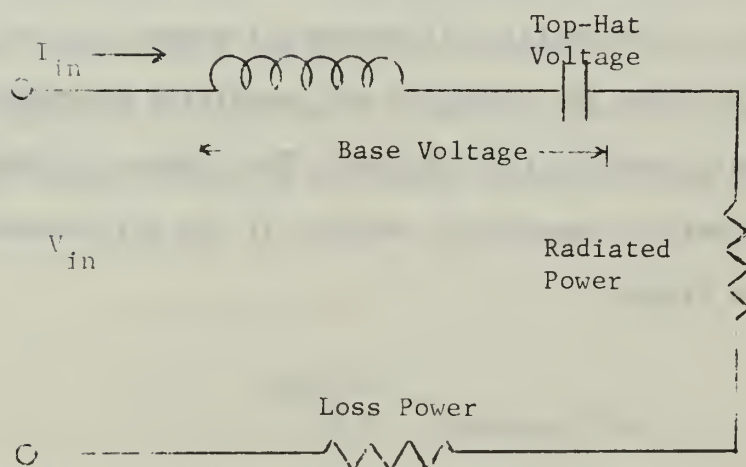


Figure 3. Voltages and Power

across the capacitive reactance (Figure 3) and the total aerial reactance are the "top-hat" and "base" voltages respectively. Note that the voltages may be expressed directly in terms of the quality factor for the respective reactances, when the aerial is tuned to resonance.

$$V_{\text{top-hat}} = Q_{\text{ant}} V_{\text{in}} \quad \dots(3)$$

$$V_{\text{base}} = Q_{\text{downlead}} V_{\text{in}} \quad \dots(4)$$

where V_{in} = voltage applied to the series circuit

Q_{downlead} = Q of the downlead or total reactance, defined similarly to Equation (1)

Another problem is corona which takes place just before breakdown occurs. Corona develops at high voltage points which are physically near points at ground potential, and it may occur at the endpoints of the top-hat, the base of the downlead, cable connections, sharp bends, and at points where the wires may be frayed or nicked. High rf noise is generated and the aerial circuit is detuned. Corona rings and the caging or bundling of cables may be used for protection.¹⁴

The aerial self-resonant frequency is the series resonant condition when the inductive and capacitive reactances are equal and is usually outside the VLF band. The top-hat provides the major part of the aerial capacitance, without it the self-resonant frequency would be even higher.

$$f_{\text{self-resonant}} = \frac{1}{2\pi \sqrt{L C}} \quad \dots(5)$$

As the aerial capacitance is increased the Q will decrease and the bandwidth increase. The effective height will also increase and with it the radiation resistance.⁹ The top-hat voltage (a function of

radiation resistance and capacitive reactance) will tend to decrease. Thus the greater the top-hat capacitance the better the aerial will perform.

The aerial efficiency is the ratio of the radiation resistance to the sum of all resistances in the circuit. Since the radiation resistance is of the order of one ohm, all loss resistances must be equal to or less than this to obtain an efficiency of 50% or greater. In practice this can be done by using large diameter cables to reduce losses.

$$\text{Efficiency} = \frac{R_{\text{radiation}}}{R_{\text{radiation}} + R_{\text{loss}}} \quad \dots(6)$$

Equation (6) is good only at a specific frequency since the radiation resistance will normally increase with frequency. The lower the operating frequency, the more carefully all losses must be considered.

In summary, the normal VLF aerial is much shorter than an electrical quarter wavelength and is electrically lengthened through the use of top-loading capacitance. It is physically large (mainly due to the top-hat), has a high Q and narrow bandwidth. The achieved efficiency will in practice be close to 50%, and limitations on power handling ability is usually caused by breakdown voltages across the reactive elements.

B. Impedance Matching Networks

Maximum power transfer between a generator and its load occurs when the load resistance is equal to the generator resistance. If the generator impedance has a reactive component then the load should have a reactance of equal value but opposite sign. The generator and load impedances are then "conjugates."

In radio frequency applications the generator can usually be made purely resistive, and thus the load should be a pure resistance. But even with a pure resistance load maximum power transfer may not occur. For example, if a vertical quarter wavelength radiator, half-wave dipole or folded half-wave dipole are each resonant at the same frequency their input impedances are purely resistive. But their magnitudes are 36, 72, and 300 ohms respectively. If the generator has a resistance of 50 ohms, maximum power transfer cannot be directly accomplished with any of these systems.

A network may be added between the generator and antenna which will allow maximum power transfer. The generator sees the network and antenna combination as a 50 ohm resistive load, and the antenna looking into the network-generator combination sees a pure resistance source of the proper magnitude. The network which meets these requirements is known as an impedance matching network.

It is desirable to introduce as little insertion loss as possible, so the network should be "lossless." If resistors are used in the network such a requirement cannot be met, but by using high quality reactive components the lossless case can be closely approximated. No component is ideal, but the ohmic resistance can be made very small, and in any case, much, much less than the alternating current reactance.

VLF aeriels have been shown to have a resistive component in their input impedance, and since inductive and capacitive parameters are present, also a reactance term; except at the precise resonant frequency. When operation at other than resonance is desired the reactance term will appear and increase in magnitude the further operation is attempted from resonance. Below resonance the reactance will be capacitive; above resonance inductive. In the following discussion it will therefore be assumed that the aerial is a complex impedance load.

Impedance matching networks are built using the basic properties of series and parallel circuits. In Figure 4 two circuits with identical behavior at the same frequency are shown, the second being the parallel form of the first. The parameters are defined as follows:

$$Z_s = R_s + jX_s \quad \dots(7)$$

$$Z_p = R_p + jX_p \quad \dots(8)$$

where

Z_s = impedance of series circuit

Z_p = impedance of parallel circuit

R_s = series resistance term

jX_s = series reactance term

R_p = parallel resistance term

jX_p = parallel reactance term

The impedance of the two circuits is the same at the same frequency. The quality factor of "Q" defined in Equation (1.a) for the aerial may now be generalized to apply to both the series and parallel circuits. At the operating frequency, both circuits have identical "Q's."

$$Q_s = \frac{|jX_s|}{R_s} \quad \text{for the series circuit} \quad \dots(9)$$

$$Q_p = \frac{R_p}{|jX_p|} \quad \text{for the parallel circuit} \quad \dots(10)$$

Equations for converting between series and parallel circuits are given below:

<u>Parameter</u>	<u>"Q" Equations</u>	<u>Reactance Equations</u>	
R_p	$= R_s (Q_s^2 + 1)$	or $R_s [1 + (\frac{X_s}{R_s})^2]$	$\dots(11)$

jX_p	$= jX_s [\frac{Q_s^2 + 1}{Q_s^2}]$	or $jX_s [1 + (\frac{R_s}{X_s})^2]$	$\dots(12)$
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R_s	$= \frac{R_p}{(Q_p^2 + 1)}$	or $\frac{R_p}{[1 + (\frac{R_p}{X_p})^2]}$	$\dots(13)$
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jX_s	$= \frac{jX_p}{[\frac{Q_p^2 + 1}{Q_p^2}]}$	or $\frac{jX_p}{[1 + (\frac{R_p}{X_p})^2]}$	$\dots(14)$
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Either the "Q" equations or the reactance equations may be used in transforming from one circuit to another. When the reactance of a series circuit is greater than the resistance by a factor of 10 or more (or less by a factor of 10 for the parallel circuit) then the equations above may be simplified.

R_p	$\approx (Q_s)^2 R_s$	or $R_s (\frac{X_s}{R_s})^2$	$\dots(15)$
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jX_p	$\approx jX_s$	or jX_s	$\dots(16)$
--------	----------------	-----------	-------------

R_s	$\approx \frac{R_p}{(Q_p)^2}$	or $\frac{R_p}{(\frac{R_p}{X_p})^2}$	$\dots(17)$
-------	-------------------------------	--------------------------------------	-------------

jX_s	$\approx jX_p$	or jX_p	$\dots(18)$
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Examination of equations (15) through (18) shows that an error of 1% occurs when Q is 10; the error decreases as Q increases.

If the circuits in Figure 4 are to be modified to be purely resistive an additional reactance is needed. Thus if a reactance of the same magnitude as X_s but of opposite sign is added to the series circuit, the reactance will sum to zero and a pure resistance results. By the same token, adding a reactance which is the conjugate of X_p to the parallel circuit will give a resultant impedance equal to R_p .

The above operations may be combined to produce different results. If a reactance of magnitude X_s but of opposite sign than X_p is added in series to the parallel circuit, then the total impedance becomes R_s . This may be seen by first transforming the parallel circuit to its series equivalent and then adding the new reactance. Alternately, if a reactance of magnitude X_p with sign opposite X_s is added in parallel to the series circuit, R_p is the resultant impedance. These results are shown in Figure 5 and summarized below:

<u>Circuit</u>	<u>Added Reactance</u>	<u>Connect In</u>	<u>Resultant R</u>
Series	$- jX_s $	series	R_s
Series	$- jX_p $	parallel	R_p
Parallel	$- jX_s $	series	R_s
Parallel	$- jX_p $	parallel	R_p

The procedures above are the basis for a common type of impedance matching networks. Methods for connecting a reactance to a circuit and obtaining either the series or parallel value of the resistance have been shown. But suppose a resistance value other than R_s or R_p is desired, but still without any reactive terms present. This can be done but may require a second reactance to be used.

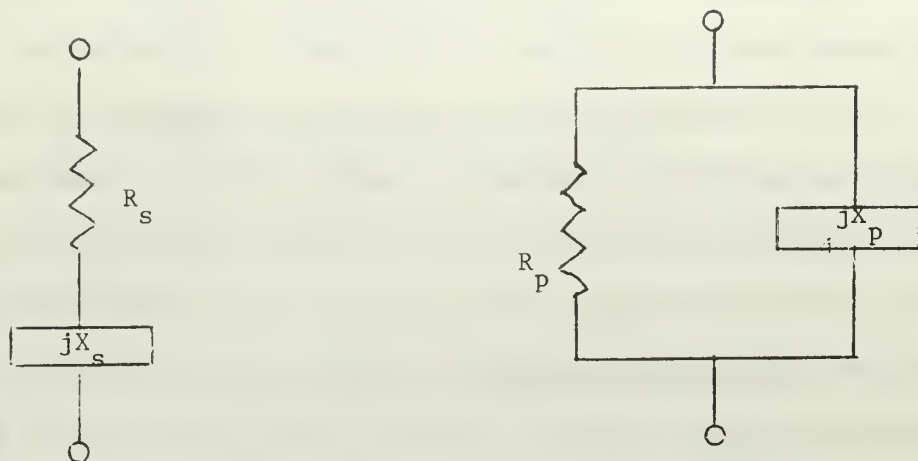


Figure 4. Basic Series and Parallel Circuits

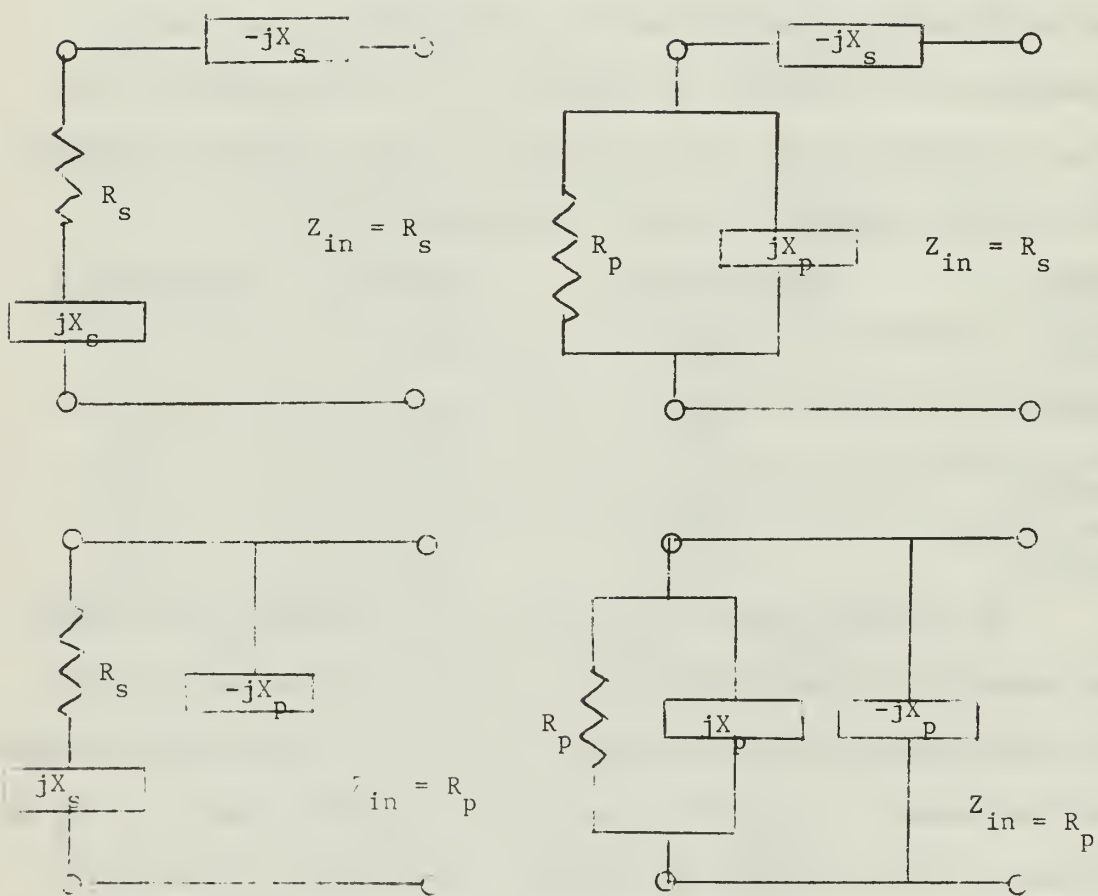


Figure 5. Basic Matching Circuits

Following the work of Fowler and Kemp, the circuit shown in Figure 6 is used.¹⁵ With the circuit broken at A looking to the right, a resistance R_p is seen. Similarly, if the circuit is broken at C, looking to the left R_s is seen. Thus resistances R_s and R_p are matched to each other. However, at cut B the circuit to the right is $R_s - jX_s$; to the left is R_p in parallel with jX_p . If the series circuit to the right is transformed to its parallel equivalent, R_p is in parallel with $-jX_p$. The left and right hand circuits are seen to have equal resistive components (R_p) but conjugate reactances (equal magnitude but opposite signs). The parallel circuit could have been transformed to a series circuit and given a resistance of R_s at cut B. No matter what form is used, the impedances at B are seen to be conjugates.

From Equation (11) R_p is seen to be always greater than R_s . Then to match two resistances the higher resistance may be connected across the shunt arm of the network to the right of cut A. The two reactances are adjusted to give conjugate impedances at cut B. If the two loads to be matched have reactive as well as resistive terms, then the reactances in Figure 6 are first adjusted to make the loads purely resistive and then modified to meet the matching requirements. Due to its physical shape, the network between cuts A and C in Figure 6 is known as an "L" network.

Figure 7 shows two other forms of matching networks, the Tee and the Pi. These networks are seen to be the combination of two L sections combined in different ways. They may in fact be designed as two L sections and then combined.

When pure resistances are matched the two reactances in the L network must have opposite signs, in the Tee and Pi this is extended

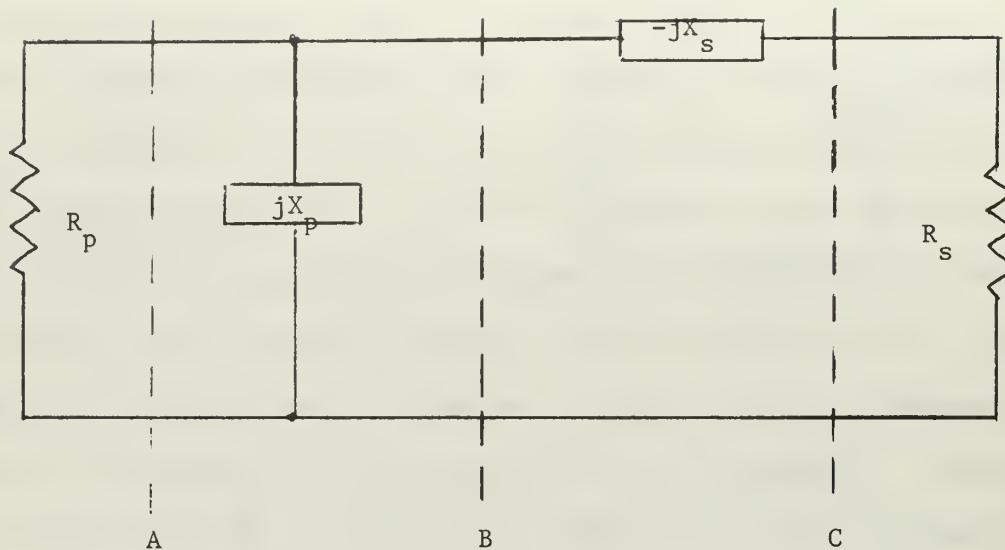


Figure 6. Basic "L" Network

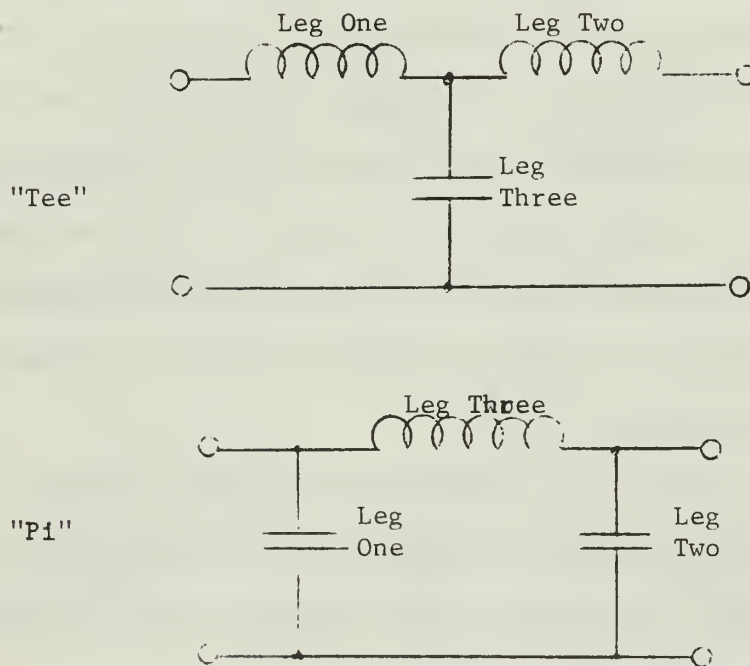


Figure 7. Tee and Pi Networks

to having one element different from the other two. These restrictions do not apply if the loads have reactive components.

If the Tee and Pi networks are constructed as shown in Figure 7 then they are called symmetrical. The inductors and capacitors may be interchanged in either network without destroying the symmetry. It should also be clear from Figure 7 that the Tee and Pi networks shown are duals, and at a given frequency one may be directly substituted for the other.

Tables I, II, and III give the equations needed for designing impedance matching networks of the L, Tee, and Pi forms respectively. In all cases the two impedances to be matched are assumed to be purely resistive. If they are not, the networks should be designed on the assumption that they are, and then the network legs may be modified as required.

An alternate method of computing values for the Tee and Pi networks is to consider each as a lumped parameter equivalent of a quarter-wave transmission line. Such a line is often used for impedance matching, and has the additional property of inverting the load as seen at the input network terminals. That is, if a load which has infinite impedance (open circuit) is connected to the Tee, reactances X_a and $X_d - X_e$ are seen to be a series resonant circuit, which has zero impedance. Conversely, a zero impedance load (short circuit) causes X_b and $X_d - X_e$ to be a parallel-resonant circuit which has an infinite impedance. The Pi network may be similarly described.

TABLE I

L SECTION DESIGN EQUATIONS

Diagram	
Assumptions	$R_b > R_a$ Both R_a and R_b are purely resistive.
Given	R_a , R_b
Equations	$X_a = \pm R_a \sqrt{\frac{R_b}{R_a} - 1}$ $\text{or } \pm \sqrt{R_a R_b - R_a^2} \quad \dots(19)$ $X_b = \mp \frac{R_b}{\sqrt{\frac{R_b}{R_a} - 1}}$ $\text{or } \mp \frac{R_a R_b}{X_a} \quad \dots(20)$ <p>Note: X_a and X_b are taken with opposite signs.</p>

TABLE II

TEE NETWORK DESIGN EQUATIONS

Diagram		
Assumptions	$R_b > R_a$ Both R_a and R_b are purely resistive. $R_c > \text{both } R_a \text{ and } R_b$	
Given	R_a, R_b, R_c	
Equations	$X_a = \pm R_a \sqrt{\frac{R_c}{R_a} - 1} \quad \dots(21)$ $X_b = \pm R_b \sqrt{\frac{R_c}{R_b} - 1} \quad \dots(22)$ $X_c = \frac{X_d X_e}{X_d + X_e} \quad \dots(23)$ $X_d = \mp \frac{R_c}{\sqrt{\frac{R_c}{R_a} - 1}} \quad \dots(24)$ $X_e = \mp \frac{R_c}{\sqrt{\frac{R_c}{R_b} - 1}} \quad \dots(25)$ <p>Note: X_a and X_d have opposite signs. X_b and X_e have opposite signs.</p>	

Given	R_a, R_b, X_a
Equations	$R_c = R_a \left[1 + \left(\frac{X_a}{R_a} \right)^2 \right] \quad \dots(26)$
	$X_d = X_a \left[1 + \left(\frac{R_a}{X_a} \right)^2 \right] \quad \dots(27)$
	X_b Use equation (22)
	X_c Use equation (23)
	X_e Use equation (25)
Given	R_a, R_b, X_b
Equations	$R_c = R_b \left[1 + \left(\frac{X_b}{R_b} \right)^2 \right] \quad \dots(28)$
	X_a Use equation (21)
	X_c Use equation (23)
	X_d Use equation (24)
	X_e Use equation (25)
Given	R_a, R_b, X_c
Equations	$X_a = -X_c \left[1 \pm \sqrt{\frac{R_a}{R_b} - \left(\frac{R_c}{X_c} \right)^2} \right] \quad \dots(29)$
	$X_b = -X_c \left[1 \pm \sqrt{\frac{R_b}{R_a} - \left(\frac{R_b}{X_c} \right)^2} \right] \quad \dots(30)$
	X_d Use equation (24)
	X_e Use equation (25)
	X_c Use equation (26) or (28)

TABLE II (continued)

TABLE III

PI NETWORK DESIGN EQUATIONS

Diagram	
Assumptions	$R_b > R_a$ Both R_a and R_b are purely resistive. $R_c < \text{both } R_a \text{ and } R_b$
Given	R_a, R_b, R_c
Equations	$X_a = \pm \frac{R_a}{\sqrt{\frac{R_a}{R_c} - 1}} \quad \dots(31)$ $X_b = \pm \frac{R_b}{\sqrt{\frac{R_b}{R_c} - 1}} \quad \dots(32)$ $X_c = X_d + X_e \quad \dots(33)$ $X_d = \pm R_c \sqrt{\frac{R_a}{R_c} - 1} \quad \dots(34)$ $X_e = \pm R_c \sqrt{\frac{R_b}{R_c} - 1} \quad \dots(35)$ <p>Note: X_a and X_d have opposite signs. X_b and X_e have opposite signs.</p>

Given	R_a, R_b, X_a
Equations	$X_d = \frac{X_a}{1 + \left(\frac{X_a}{R_a}\right)^2} \quad \dots(36)$
	$R_c = \frac{R_a}{1 + \left(\frac{R_a}{X_a}\right)^2} \quad \dots(37)$
	X_b Use equation (32)
	X_c Use equation (33)
	X_e Use equation (35)
Given	R_a, R_b, X_b
Equations	$X_e = \frac{X_b}{1 + \left(\frac{X_b}{R_b}\right)^2} \quad \dots(38)$
	$R_c = \frac{R_b}{1 + \left(\frac{R_b}{X_b}\right)^2} \quad \dots(39)$
	X_a Use equation (31)
	X_c Use equation (33)
	X_d Use equation (34)
Given	R_a, R_b, X_c
Equations	$X_a = -R_a X_c / \left[R_a \pm \sqrt{R_a R_b - X_c^2} \right] \quad \dots(40)$
	$X_b = -R_b X_c / \left[R_b \pm \sqrt{R_a R_b - X_c^2} \right] \quad \dots(41)$
	X_d Use equation (34)
	X_e Use equation (35)
	R_c Use equation (37) or (39)

TABLE III (continued)

The networks described, although designed for impedance matching, will also act as filters. In work at radio frequencies one is usually interested in suppressing higher frequency harmonics, and thus a low pass filter response is desired. Or there may be undesirable sidebands produced by modulation of the basic carrier system, and then a bandpass filter which would discriminate against unwanted frequencies would be called for.

The choice of which impedance matching network to use is based on a number of factors. What is the ratio of the two resistances to be matched? What type of reactance do the loads have, is it large or small, and how may it best be cancelled out? Will one of the loads vary significantly with frequency or will the resistance remain fairly constant and only the reactance vary? How many components are available for the network? What power and breakdown voltage ratings must be met? What magnitude of stray capacitance will be encountered? (The Pi network with capacitors for the legs would be useful here.) What about ease of operation; can tuning be quickly and accurately accomplished by the personnel involved?

Additionally, what power will be dissipated by the network? The proper choice of network may mean a substantial improvement in efficiency. Terman points out that "for a given [impedance] transformation ratio, the "L" section has a lower loss than either the Tee or Pi."⁴

Example:

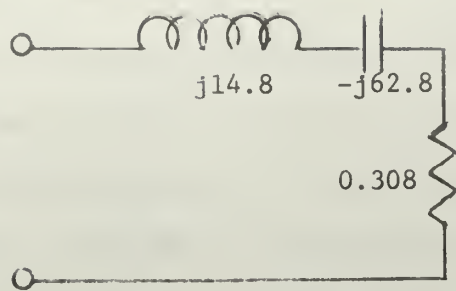
As a particular example of impedance matching, the aerial circuit shown in Figure 2 and redrawn in Figure 8(A) will be used. The impedance values shown are typical of a VLF aerial, and are chosen to

show the range of magnitudes encountered. It is desirable to use a matching network to obtain a purely resistive output of 12.5 ohms at the operating frequency.

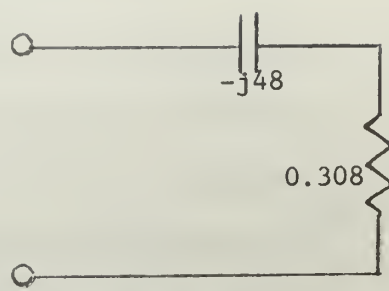
A number of variations of this circuit are possible. In Figure 8(B) the reactances have been combined, since this is what a radio frequency bridge connected to the input terminals would see. It is also possible to take the capacitor and resistor as a sub-network and convert them to their parallel equivalent circuit, as shown in part C. Since the Q of this circuit is greater than 10 by Equation (9), the transformation may be made using Equations (11) and (12). A similar procedure yields the circuit shown in part D. The parallel circuit of part E is determined from the circuit of part B.

Since the desired resistance at resonance is 12.5 ohms, and such a value does not appear from any of the manipulations in Figure 8, the most direct approach to the desired result would be to use the circuit in part B and add a matching network. Figure 9(A) shows such an approach. First a reactance of equal magnitude but opposite sign is added in series to produce a pure resistance. Then a simple L network is designed to convert the 0.308 ohm load to the desired 12.5 ohms. When constructed, the series inductance would be included in X_a so that the completed network would be to the left of the dashed line. Values for the L network are found from Equations (19) and (20).

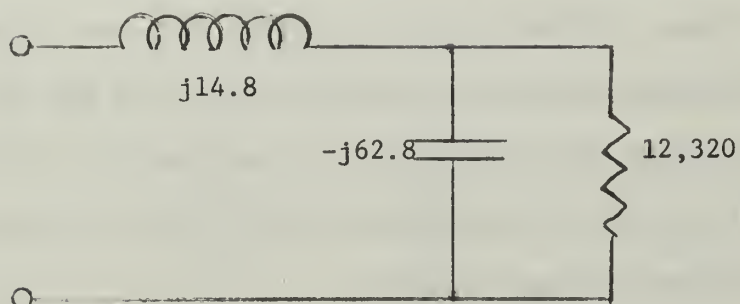
A second approach would be to use the parallel form of the aerial circuit. Here the new inductive reactance is connected in parallel and the L networks used to convert 7,550 ohms down to 12.5 ohms. Again the completed L network would be the circuit to the left of the dashed line.



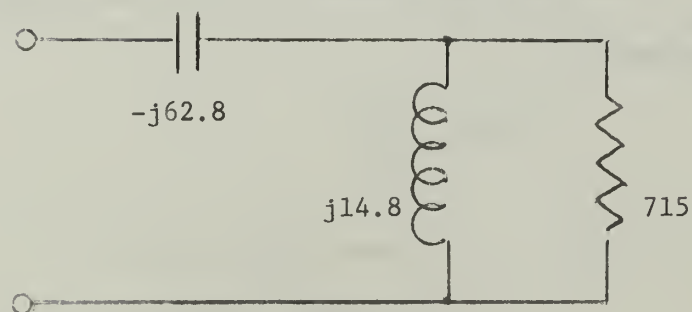
A



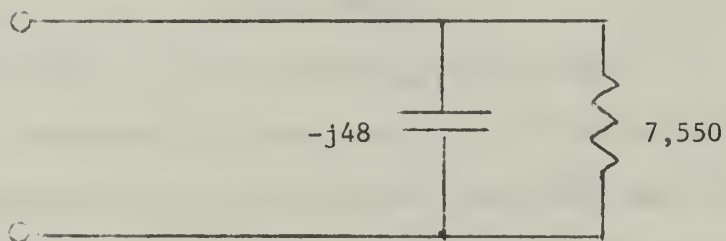
B



C



D



E

Figure 8. Variations of Basic Aerial Circuit

The networks in Figure 8, parts C and D may also be used. If it is desired to have a pure resistance at resonance the total series reactance must have the same magnitude but opposite sign of the parallel reactance. In both of these cases it is seen that an additional inductive reactance of j48 ohms is required and the total network resistance will be the same as the series resistance, 0.308 ohms.

There is also the possibility of using some form of transformer arrangement to achieve the desired 12.5 ohms. In fact a single inductor could be used as an autotransformer if the taps were properly chosen. If the circuit in Figure 8(E) has an inductive reactance of j48 ohms connected in parallel across it the result will be a parallel resonant tank circuit with a resistance of 7,550 ohms. If the inductor is tapped as shown in Figure 9(C) then 12.5 ohms will be measured between the tap and ground.

The relation between turns and impedance for an autotransformer is given by:

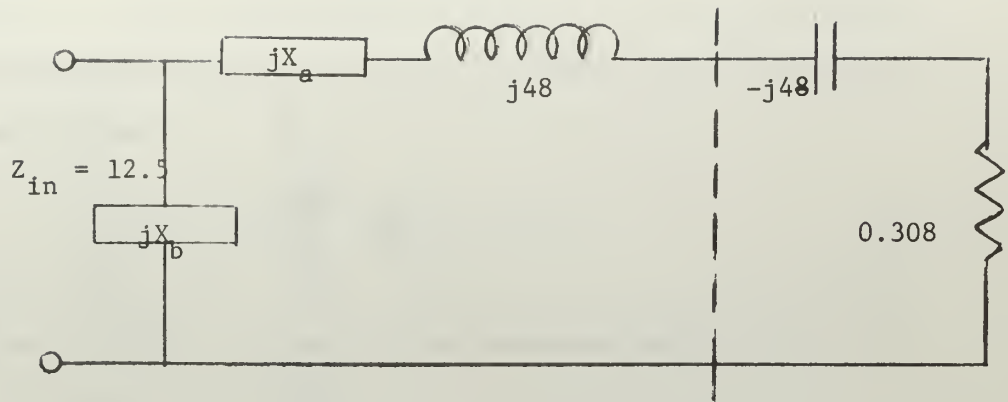
$$N^2 = \frac{Z_1}{Z_2} \quad \dots(42)$$

where Z_1 = primary impedance

Z_2 = secondary impedance

N = turns ratio

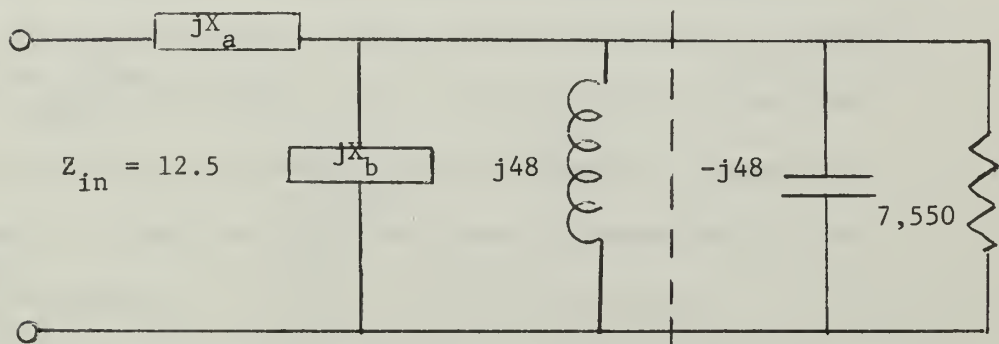
With Z_1 and Z_2 equal to 12.5 and 7,550 ohms respectively, N is found to be 1/24. A total inductive reactance of j48 ohms is needed, and since inductance varies directly with the number of turns, a selection of the tap such as that shown in Figure 10 can be made. Here it should be noted that the same results may be obtained by considering the circuit shown in Figure 8(B) to be made into a series resonant circuit.



A

$$jX_a = \pm [1.935]$$

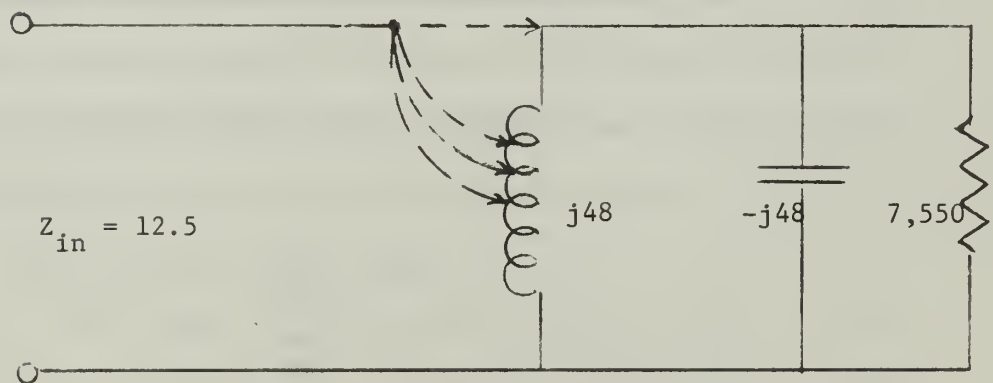
$$jX_b = \mp [1.99]$$



B

$$jX_a = \pm [30.65]$$

$$jX_b = \mp [3080]$$



C

Figure 9. Various Matching Arrangements

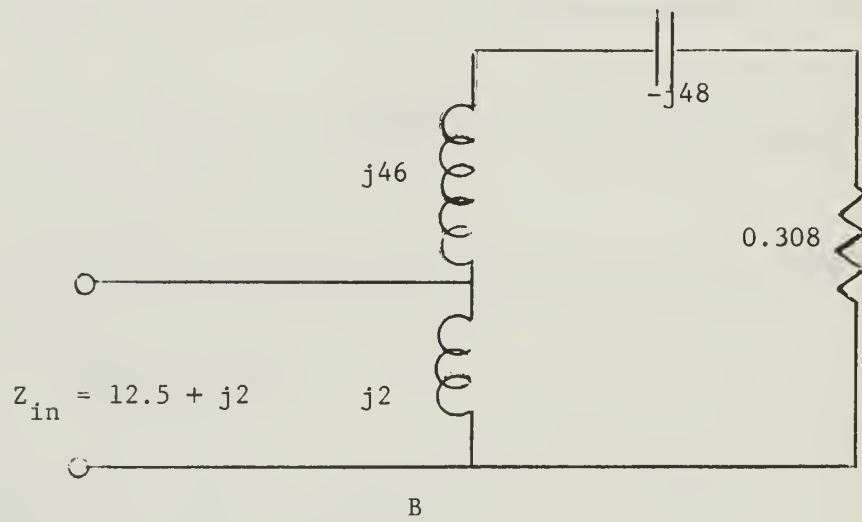
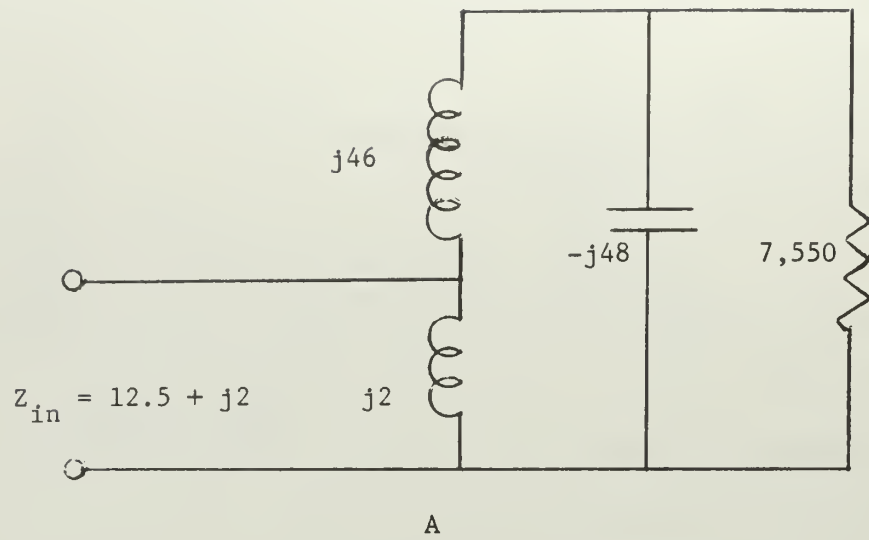


Figure 10. Autotransformer Matching

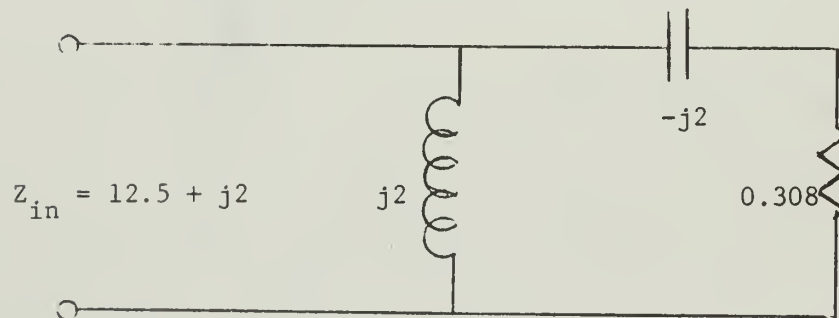


Figure 11. Simplified Circuit

Figure 11 shows the resultant circuit. It is more convenient to consider the series form of the aerial circuit, which has an input impedance defined as:¹⁶

$$Z_{in} = \frac{R(X_L)^2 + j[X_L R^2 - \frac{L}{C}(X_L - X_C)]}{R^2 + (X_L - X_C)^2} \quad \dots(43)$$

At resonance the reactance terms will partially cancel, and the simplified form below results:

$$Z_{in} = \frac{(X_L)^2}{R} + jX_L \quad \dots(44)$$

Thus by tapping the coil to lower the input resistance a reactance term has been added. (It should be noted that the proper tap on the coil is most easily found by Equation (44), since the resistive part of Z_{in} and the value of R are shown. X_L may be computed, and the total coil is merely equal in magnitude to the capacitive reactance.)

Since the reactance is small it seems apparent that at some frequency other than resonance it will become zero. Figure 12 shows the general circuit, where the series capacitive reactance is assumed greater than the series inductive reactance at resonance. If the series sum is denoted by $-jX_{sum}$, the input admittance for the circuit is given by:

$$Y_{in} = \frac{R}{R^2 + X_{sum}^2} + j[\frac{X_{sum}}{R^2 + X_{sum}^2} - \frac{1}{X_{L_2}}] \quad \dots(45)$$

The real part of the admittance at resonance should be 1/12.5 mhos, so solving for X_{sum} :

$$X_{sum} = \sqrt{R(12.5 - R)} \quad \dots(46)$$

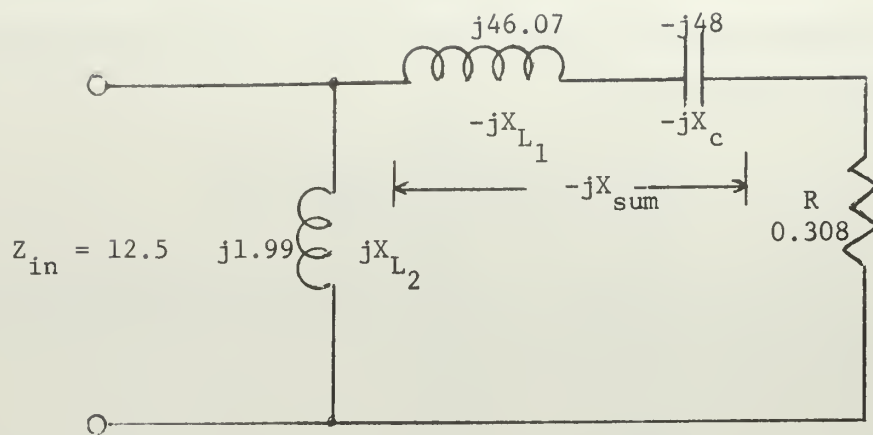


Figure 12. Zero Reactance Circuit

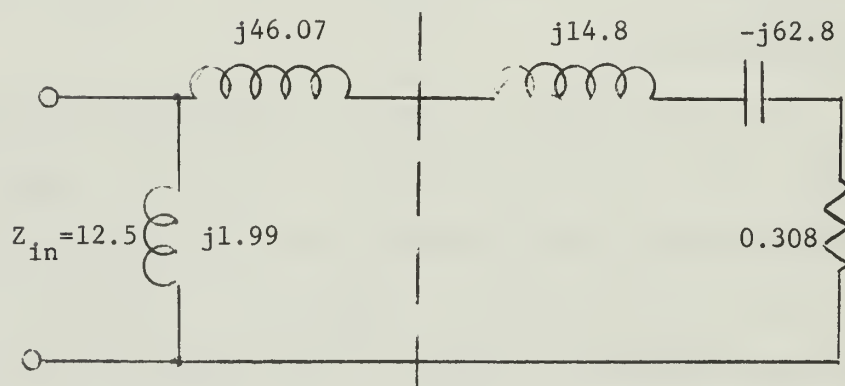


Figure 13. Final Circuit

With an R of 0.308 ohms the positive root for the magnitude of X_{sum} will be used, which has a value of 1.93 ohms. It is now necessary that the reactive part of the admittance be zero so solving for the parallel inductive reactance:

$$X_{L_2} = \frac{R^2 + X_{sum}^2}{X_{sum}} \quad \dots(47)$$

This inductive reactance is found to be 1.99 ohms, and the complete circuit may now be finished as shown in Figure 13. Comparing Figure 13 with Figure 10(B), the value of the inductance has been increased very slightly, but the total input impedance of the circuit at resonance is now purely resistive.

Examination of the circuit in Figure 13 shows the part to the left of the dashed line to be a L network. When values for the L network shown in Figure 9(A) are compared with those in the final circuit, they are seen to be the same. Thus after some involved mathematics the same results as those obtained from the comparatively simple Equations (19) and (20) are determined.. Several important conclusions can be drawn from this, when designing a matching network.

First compare the magnitude of the desired resistance (12.5 ohms) with the values obtained from manipulating the aerial network. As a series circuit the aerial had 0.308 ohms resistance, with the RC parallel configuration the resistance was 12,320 ohms, with the RL arrangement 715 ohms, and with the reactances summed and then formed into a parallel circuit 7,550 ohms. Since the series value of 0.308 ohms is the closest to 12.5 ohms, use the series circuit.

Next compute the values for the L, Tee and Pi networks which will make the desired transformation. At this time neglect the aerial

reactance completely. The L network will probably be the easiest to use although the wider tuning range available or size of components may show one of the others to be preferable.

Finally include the aerial reactance (here $-j48$ ohms) in the circuit and modify the impedance matching network values to achieve the desired values. Choose variable tuning elements for the network so that any variation in component values in the final circuit may be compensated for.

One additional word about the circuit shown in Figure 13; it is simple and requires only two components, the values are within easily obtainable ranges, and the aerial is provided with a direct current path to ground which provides good protection against lightning and other electrical discharge.

C. Transformer Coupling

A coupling method not mentioned previously involves the use of transformers. They may be constructed to meet many different impedance ratios, but generally the magnitude of the loads must fall into a relatively narrow range. For example, a transformer with an impedance ratio of 10:1 and designed to match 500 to 50 ohms probably would not work well if used to match 50,000 to 5,000 ohms even though the ratio is the same.¹⁷

Transformers utilize iron cores at low frequencies, but at radio frequencies losses in the core become excessive and air cores are used. Satisfactory operation is usually limited to fairly small deviations from the center design frequency.

At radio frequencies transformers find use where a relatively constant impedance ratio is involved, only small deviations in frequency take place, and as little attenuation as possible is desired. An additional advantage is that there is no direct electrical connection between the primary and secondary circuits. Energy transfer is made through magnetic coupling, a fact of some importance where high direct current voltages such as those in power amplifiers are present.

A transformer wound with low resistance wire may be considered as a lossless two-port reciprocal network. If Z_{11} is defined to be the input impedance, Z_{22} the output impedance looking back into the network, and Z_{12} equal to Z_{21} to be the transfer impedances, then the impedance matrix for the transformer may be written:

$$Z = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \quad \dots(48)$$

Considering only the transformer in Figure 14:

$$E_1 = Z_{11} I_1 + Z_{12} I_2 \quad \dots(49)$$

$$E_2 = Z_{21} I_1 + Z_{22} I_2 \quad \dots(50)$$

If the transformer is lossless and terminated in an impedance Z_{load} , then:

$$E_2 = -I_2 Z_{load} \quad \dots(51)$$

By manipulation of equations (49), (50), and (51), the input impedance looking into the transformer will be:

$$\begin{aligned} Z_{in} &= \frac{E_1}{I_1} \\ \text{or } Z_{in} &= Z_{11} - \frac{(Z_{12})^2}{Z_{22} + Z_{load}} \end{aligned} \quad \dots(52)$$

For the lossless case, assuming no resistance in the input, output, or transfer impedances (or else the reactance is much greater than the resistance), Z_{in} may be written as:

$$Z_{in} = j\omega L_1 + \frac{(\omega M)^2}{j\omega L_2 + Z_{load}} \quad \dots(53)$$

where L_1 = primary transformer inductance
 L_2 = secondary transformer inductance
 M = mutual inductance
 ω = frequency in radians

A common application of transformer coupling is in the matching of a vacuum tube to a load. The tube may be considered as a generator in series with a high resistance, while the load is usually a much lower impedance. Such a circuit is shown in Figure 15. Examination of Equation (53) shows that the transformer-load combination may be replaced by a complex impedance (Figure 16). A capacitor is often added to the primary circuit to tune out the reactive part of the new load, and the desired impedance matching can be accomplished.

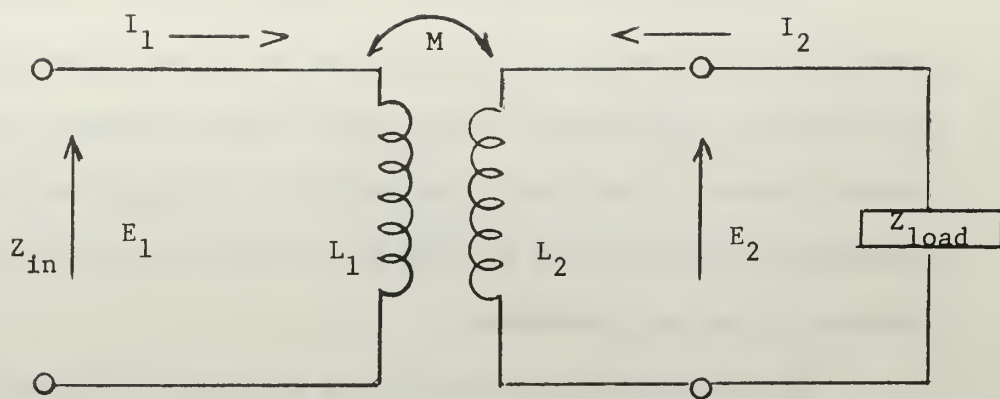


Figure 14. Basic Air-Core Transformer

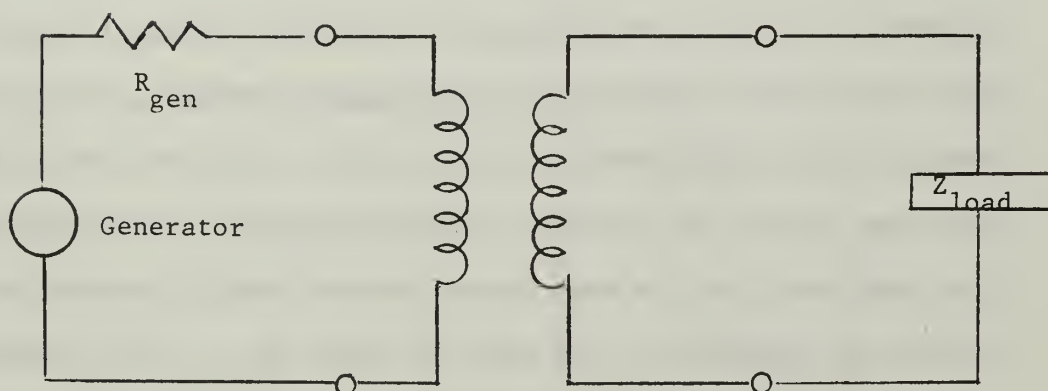


Figure 15. Vacuum Tube Source

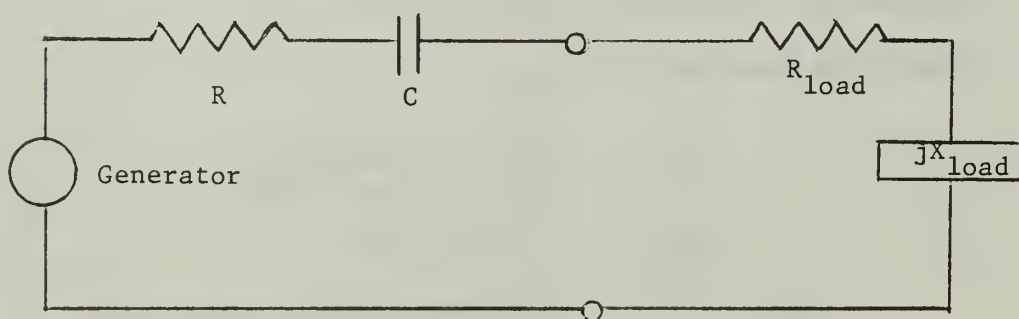


Figure 16. Equivalent Circuit For Transformer

If the vacuum tubes are to be used as power amplifiers, the power can be increased to the limits of the tube without problem, providing the transformer windings will handle the high voltage and current present. Such units can be built, although they become physically large in order to keep the losses low and prevent any voltage or current breakdowns.

When one amplifier has reached its power limit additional units may be connected. Figure 17 shows two such units. With several units on the line, the transformer secondaries and the load form a series circuit and the same circulating current will flow through all the series elements. Since all transformers are assumed identical, each will have the same voltage rise across the secondary terminals, the sum being equal to the voltage drop across the load. Then with four units on the line, Figure 18, each will supply one-fourth the voltage across the load, and with the same current as the load, in effect see one-fourth the impedance of the load, by Ohm's Law. If the transformer secondary reactances are cancelled out at the operating frequency by a series capacitance in the circuit, then in effect with multiple units each will see a load resistance equal to the original load divided by the number of units in use.

Modifying Equation (53):

$$Z_{in} = j\omega L_1 + \frac{(\omega M)^2}{j\omega L_2 + \text{Load}_n} \quad \dots(54)$$

$$\text{Load}_n = \frac{-j\omega C + Z_{load}}{n} \quad \dots(55)$$

where C = secondary series capacitance

where Load_n = portion of original load now seen by each transformer

n = number of units on the line

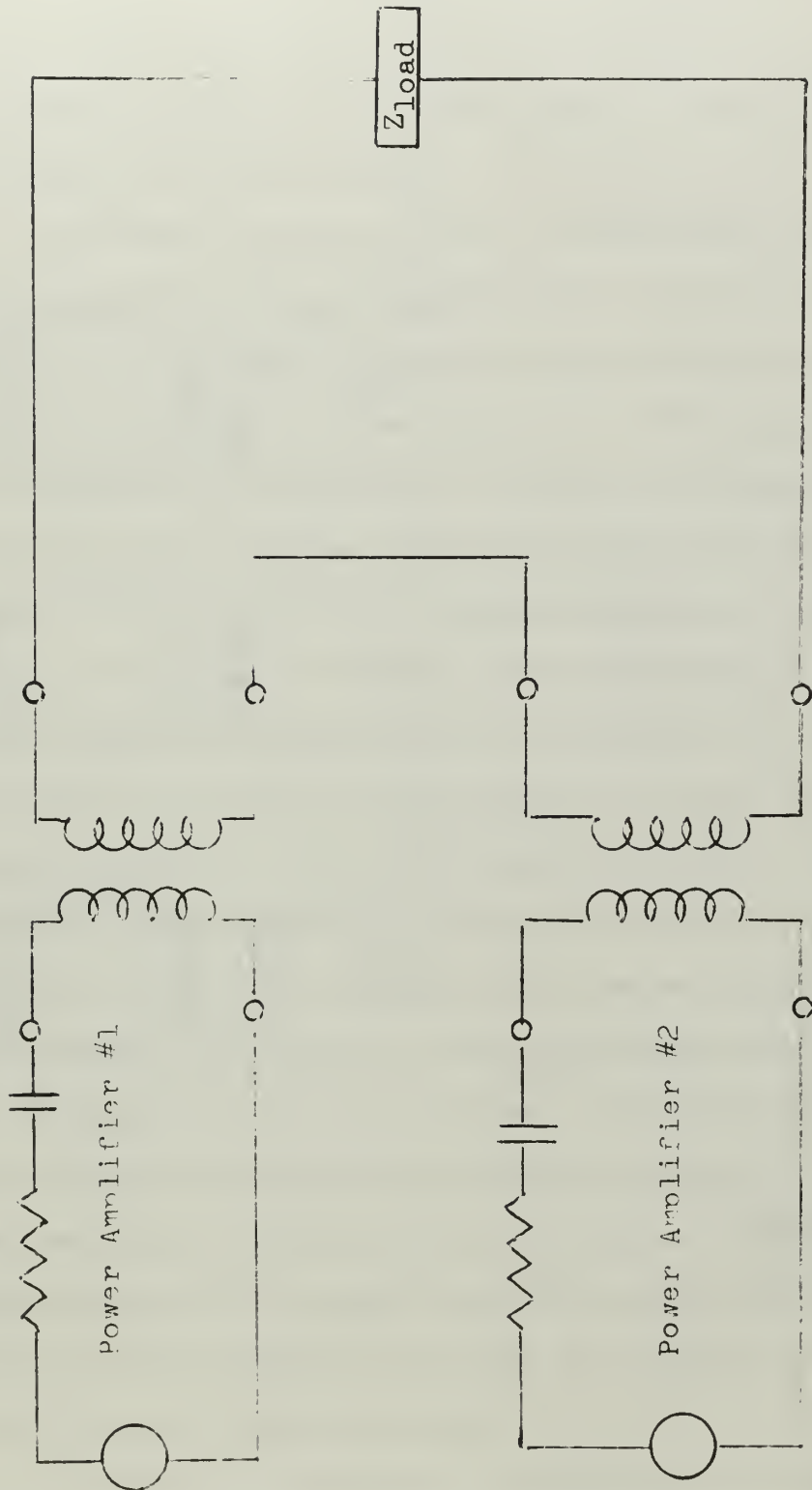


Figure 17. Two Power Amplifiers in Series

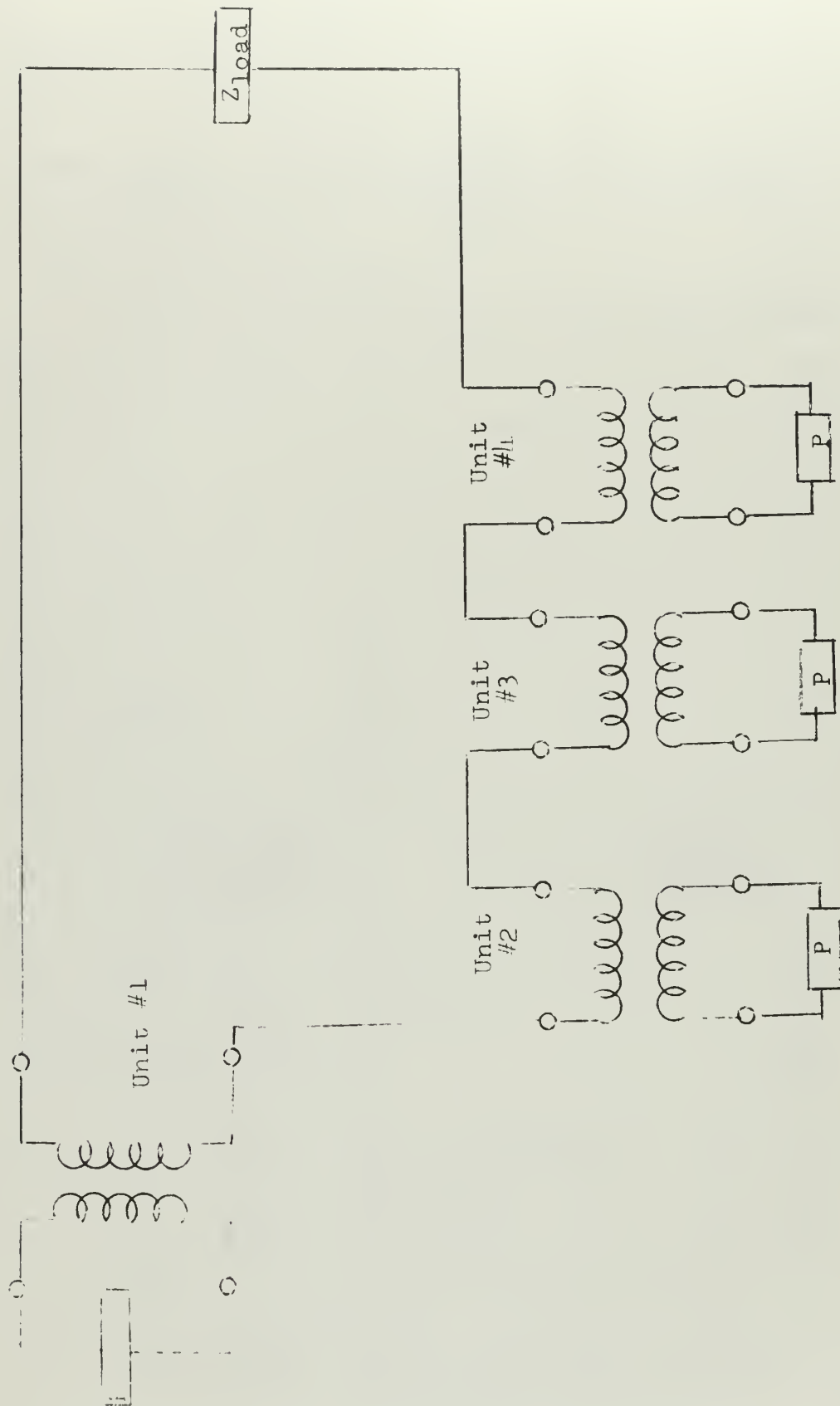


Figure 18. Four Unit Series Operation

With the secondary load of each transformer now a pure resistance, the primary circuit may also be made purely resistive by the tuning capacitor. When operation is at other than the normal operating frequency the secondary load will become reactive, but so will the primary circuit, and since all units are assumed identical all will behave in the same manner.

Two problems now appear. First, and really most important, the power amplifier tubes are operated Class C. This means that they are on for less than 180 degrees in each cycle, and the plate voltage is not a constant. This entire area of Class C operation is a very important one which should be thoroughly investigated. Such complications can be temporarily avoided here by taking the time-average or dc value of the plate voltage and assuming it constant.

Secondly, there will be some interaction among the power amplifier units, which are normally tuned up in sequence. As each additional unit is brought on the line, tuning conditions for those already present will change. Since the units have no magnetic coupling, and are fed from the same signal source, the interaction should not be too great in practice. However, the description above neglects such problems, and it is an area which requires a more detailed analysis.

The approach above is easy to use: just divide the normal load by the number of units on the line to find the load for any unit. But the restriction that each unit be identical must be completely met. The only true test is to actually compare the units which will be used under the operating conditions, for after all, this is the information which must be used in actual operation.

The effects of transformers in matching impedances has been discussed above. The term "M," shown in Figure 14 and used in

Equation (53) also has an important effect on the energy transferred from the primary to the secondary. The emphasis in the following pages will be on how this energy is transferred.

A transformer consisting of two windings may be used to couple energy from one circuit to another, without any direct electrical connection between the two. The coupling takes place when an electromagnetic flux is common to both, and a mutual inductance is created. The flux, number of turns in the primary and secondary windings, and primary and secondary current may be manipulated to determine the mutual inductance in henrys.

A form which is usually of more convenience when working with transformers already designed is given below.

$$M = k \sqrt{L_1 L_2} \quad \dots(56)$$

where M = mutual inductance

L_1 = primary inductance

L_2 = secondary inductance

k = coupling coefficient

The coupling coefficient is a function of the geometric relation between the primary and secondary coils, theoretically equal to zero when the coils are infinitely far apart and equal to one when the coils are infinitely close together and the flux generated linking both coils fully. The mutual inductance M may range from zero to a maximum given by Equation (56) when k is one. In actual practice k cannot equal one, but may be made very close to one. (The auto-transformer discussed in the Impedance Matching section has a coupling coefficient of one.)

Transformers are frequency-dependent devices, and in most applications both the primary and secondary are tuned to the same frequency. Under these conditions the effect of coupling variation may be seen directly as shown in Figure 19. Four cases are shown with the variation of primary current and secondary voltage versus frequency sketched for each case. It is also possible to show the relation between primary and secondary voltages or currents; the choice depends on the particular interests of the designer.

"Undercoupling" is defined to occur when both the primary and secondary sides of the transformer are tuned to the same frequency and an increase in coupling will cause an increase in secondary voltage.

If the coupling has been chosen such that the maximum secondary voltage is realized, then the circuits are said to be "critically coupled."

As coupling is increased beyond that required for critical coupling, the secondary response curve is seen to "widen," that is, have a small variation in magnitude as the frequency is varied about the center frequency. When the widest response is obtained without any peaks on the curve, then the circuit is "transitionally" coupled.

Coupling may be increased still further and two peaks appear. This condition is the "overcoupled" case.

Transformers operating at radio frequencies have low loss windings such that the coils have an extremely high Q and any effective resistance in the circuit comes from external parameters. Thus the system in Figure 20 will have R_1 and R_2 as the dominant resistances. The capacitors C_1 and C_2 are used to tune out the inductive reactance of the primary and secondary respectively.

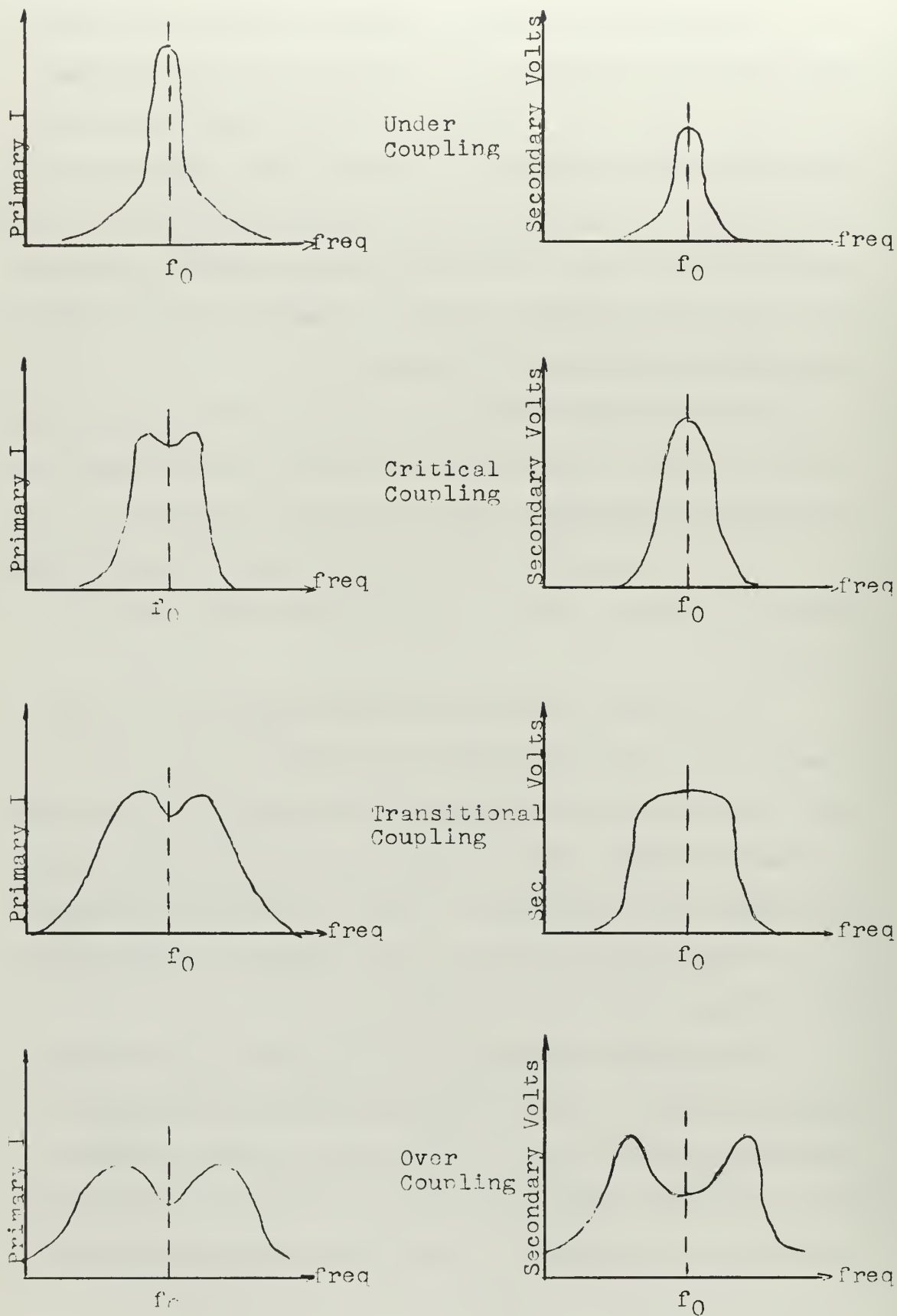


Figure 10. Primary and Secondary Responses

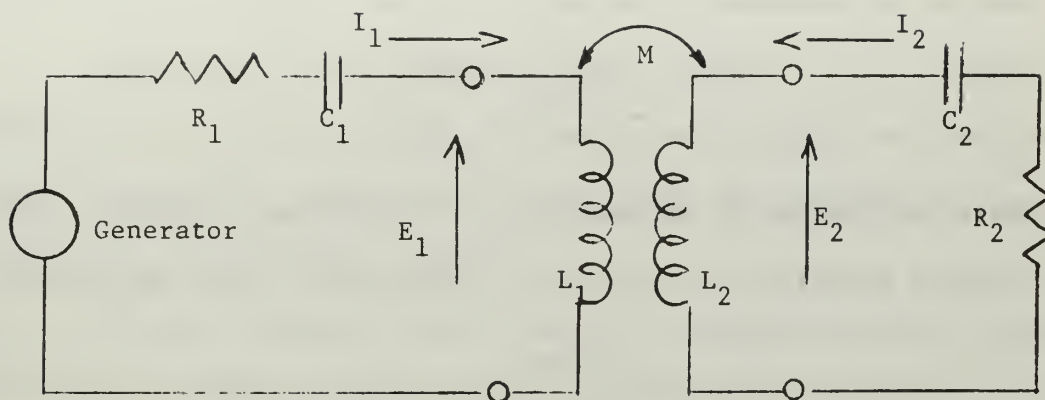


Figure 20. Basic Transformer Circuit

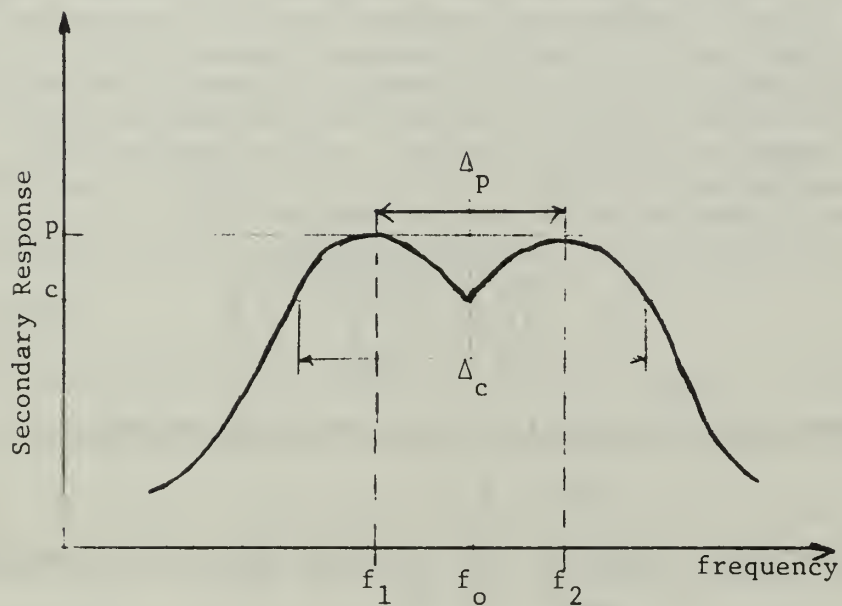


Figure 21. Double-peaked Response

The Q of the primary circuit may be defined as:

$$Q_1 = \frac{|jX_{C1}|}{R_1} = \frac{|jX_{L1}|}{R_1} \quad \dots(57)$$

and for the secondary circuit:

$$Q_2 = \frac{|jX_{C2}|}{R_2} = \frac{|jX_{L2}|}{R_2} \quad \dots(58)$$

where the reactances are measured at the resonant frequency. The coupling coefficient for critical coupling may now be defined as:

$$k_c = \frac{1}{\sqrt{Q_1 Q_2}} \quad \dots(59)$$

By substituting the expressions for Q_1 and Q_2 from Equations (57) and (58), k_c may also be defined as:

$$k_c = \sqrt{\frac{R_1 R_2}{X_{L1} X_{L2}}} \quad \dots(60)$$

It was shown earlier that the square of the mutual inductance is a factor in reflecting impedance from one side of the transformers to the other, so it is of interest to determine the value of $(wM)^2$ when there is critical coupling. Thus in Equation (56), using critical coupling as defined in Equation (60):

$$M = \sqrt{\left(\frac{R_1 R_2}{X_{L1} X_{L2}}\right) \left(L_1 L_2\right)} \quad \dots(61)$$

Solving for the mutual inductance reactance squared:

$$(wM)^2 = R_1 R_2 \quad \dots(62)$$

Examination of Equation (62) indicates that for the undercoupled case:

$$(wM)^2 < R_1 R_2 \quad \dots(63)$$

while for the transitional and overcoupled cases:

$$(wM)^2 > R_1 R_2 \quad \dots(64)$$

In radio-frequency circuits transformers are used for impedance matching and ease in coupling power from the transmitter or other source to a load. It is desirable to do this as efficiently as possible, so there should be maximum secondary power.

Bandwidth considerations are also important, since sideband intelligence should be passed while undesired harmonics are simultaneously attenuated. A compromise between power and bandwidth may be required for best overall operation.

Critical coupling occurs when the secondary voltage or current reaches its maximum possible value. At this point the primary response has two peaks, the secondary still has one peak. If the Q 's for the primary and secondary are equal then further coupling will cause the primary peaks to become more prominent and peaks will appear in the secondary. The transformer is then overcoupled.

At high frequencies where modulation sidebands are only a small percentage of the carrier frequency, the critically coupled case may be optimum. At VLF, however, the aerial circuit is very narrow in bandwidth and it is desirable to have other circuits with bandwidths greater than that for the aerial. Thus it should be determined that the transformer will not place any additional restrictions on the system response.

If the primary and secondary Q 's are made unequal, then an additional coupling response is obtained between the critical and overcoupled conditions. The primary response will show peaks as critical coupling is reached and exceeded, but the secondary response will widen somewhat before the single peak changes into double peaks.

It is desirable to determine when the secondary response will change from a single to double peaks. This can be shown to occur when:¹⁷

$$(\omega M)^2 = \frac{R_1^2 + R_2^2}{2} \quad \dots(65)$$

If the mutual inductance reactance squared is less than the term on the right then there will be only a single peak (undercoupled condition); if greater there will be two peaks (overcoupled case). If R_1 is equal to R_2 , the peak or peaks will be equal to the maximum response at critical coupling [Equations (62) and (65) are then identical]; when the two resistances are not equal the peaks for overcoupling will be less than for the critical case.

It is of interest to examine the magnitude for the various coupling conditions above. Figure 21 shows a double peaked case, and it will be assumed that R_1 and R_2 are not equal, and the primary and secondary Q's are likewise not equal. Following the work of Henney, the gain at the center frequency for any coupling coefficient whether with single or double peaks may be written:

$$\text{Gain} = \frac{M}{\omega C_1 C_2 [R_1 R_2 + (\omega M)^2]} = \frac{\omega M}{\frac{1}{Q_1 Q_2} + k^2} \quad \dots(66)$$

This magnitude is marked in Figure 21 by the dimension "c."

The maximum possible gain at the center frequency occurs with critical coupling for either single or double peaked curves. It is proportional to dimension "p" in Figure 21 and is given by:

$$\text{Gain} = \frac{X_{L1} X_{L2}}{2\sqrt{R_1 R_2}} = \frac{Q_1 Q_2 \sqrt{R_1 R_2}}{2} \quad \dots(67)$$

When the circuit is overcoupled the dimension "p" represents gain at the peaks of the two-peaked curve and is given by:

$$\text{Gain} = \frac{2M}{\omega C_1 C_2 \sqrt{(2\omega M)^2 (R_1 + R_2)^2 - (R_1^2 - R_2^2)}} \quad \dots(68)$$

The location for the peaks for the double-peaked circuit may be located by using the following equation, where f_o is the resonant frequency, and f the peak frequency.¹⁷

$$\frac{f}{f_o} = \frac{1}{\sqrt{1 \pm k \left[1 - \frac{k_c^2}{2k^2} \left(\frac{Q_1}{Q_2} + \frac{Q_2}{Q_1} \right) \right]}} \quad \dots(69)$$

The dual signs in the denominator are for the upper and lower frequencies f_1 and f_2 . The bandwidth between peaks (Δp) may be computed from Equation (69), and the bandwidth between points where the gain equals that at resonance is given by Δc :

$$\Delta c = \sqrt{2} \Delta p \quad \dots(70)$$

If a transformer has already been constructed there is an additional method of determining its coupling coefficient in the field. The primary circuit is tuned to resonance at frequency f_o with the secondary winding open. Then the secondary is shorted and the primary re-resonated, this time to the higher frequency f_s . The coefficient of coupling is then given by:

$$k = \sqrt{1 - \left(\frac{f_o}{f_s} \right)^2} \quad \dots(71)$$

where f_o = primary resonant frequency, secondary open

f_s = primary resonant frequency, secondary shorted.

In summary it may be stated that the peak gain of the secondary response curve depends on the ratio of $(\omega M)^2$ to the product of $R_1 R_2$ [Equations (62), (63), and (64)], while the shape of the response curve depends on the ratio of $(\omega M)^2$ to one-half the sum of the squared resistances [Equation (65)].

Example

At this point it is of interest to look at some examples of coupling for a radio-frequency transformer. A variable transformer with a fixed primary circuit and adjustable secondary inductance and coupling coefficient will be used. Operation will be at one frequency, but the secondary load will be different for the various cases. The basic circuit is shown in Figure 22. Parameters for the transformer primary are given below:

$L_1 = 430 \text{ } \mu\text{henry}$	$X_{L_1} = j41.9 \text{ ohms}$
$R_1 = 4.2 \text{ ohms}$	$Q_1 = 10$
$C_1 = 0.25 \text{ } \mu\text{farad}$	$f_o = 15.5 \text{ kHz}$

Table IV shows the transformer response for four distinct cases. In Case One the secondary load resistance is 20 ohms, in Case Two it is cut in half to 10 ohms. For Cases Three and Four the secondary load has been reduced to one-third and one-fourth of its initial value respectively.

In all cases the secondary Q is very low, indicating a wide bandwidth. Coupling coefficients are given as determined by Equations (59), (60), and (71). The latter equation is considered the most accurate, since it is based on measured rather than calculated values. Capacitor C_2 is used to tune the secondary alone to resonance at the operating frequency.

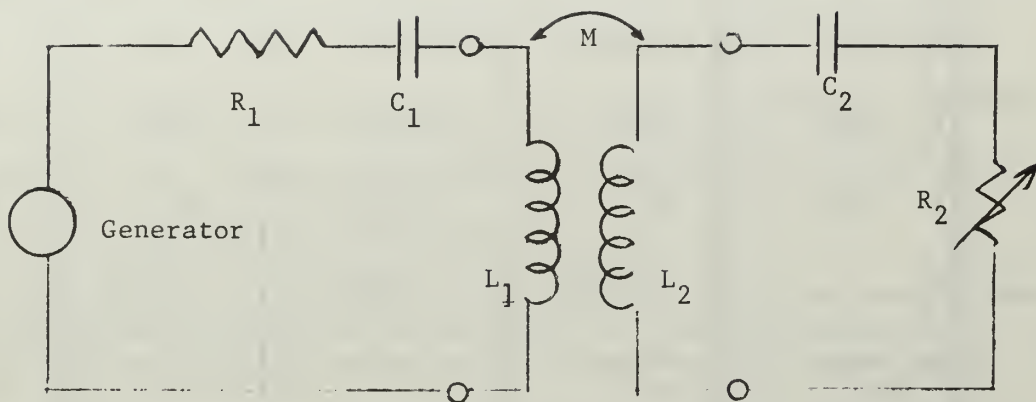


Figure 22. Circuit For Table IV

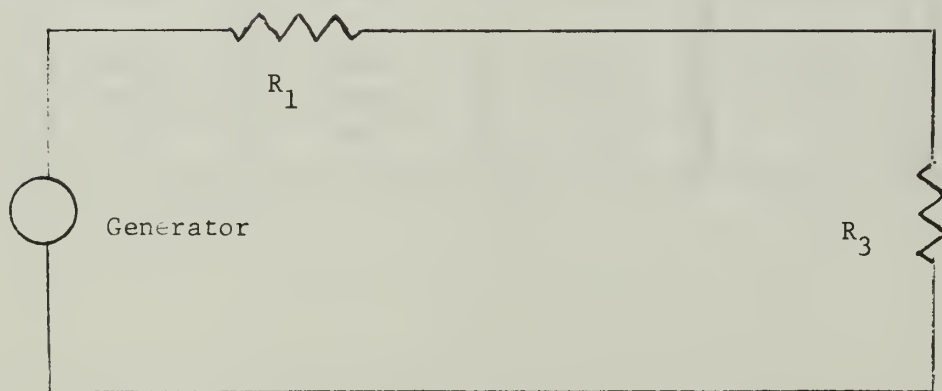


Figure 23. Resultant Circuit

TABLE IV
TRANSFORMER COUPLING ARRANGEMENTS

Case Parameter	1	2	3	4
R_2 (Ω)	20.0	10.0	6.7	5.0
L_2 (μh)	71.5	49.0	35.3	27.0
M (μh)	91.5	68.5	54.6	54.6
Q_2	0.348	0.238	0.172	0.131
jX_{L_2} (Ω)	6.95	4.77	3.43	2.63
$(wM)^2$	79.5	44.9	28.4	28.4
C_2 (μfd)	1.48	2.16	3.00	3.91
$R_1 R_2$	80.4	42.0	26.6	21.0
$\frac{R_1^2 + R_2^2}{2}$	208.8	58.8	28.9	21.3
k_c (Eqn. 59)	0.538	0.650	0.762	0.875
k_c (Eqn. 60)	0.534	0.468	0.430	0.436
k (Eqn. 71)	0.522	0.474	0.444	0.508
R_3 (Ω)	3.90	4.49	4.26	5.68

For Case One the coefficient of coupling is less than critical, Equation (63) shows slight undercoupling and the shape of the secondary response curve should be single-peaked according to Equation (65). Case Two is overcoupled by Equation (64) and will have a double-peaked curve from Equation (65). By the same equations Case Three is overcoupled but should have only one peak, a case of transitional coupling. Case Four is also a transitional form of coupling which should yield only one peak for the secondary curve.

Using Equation (53) the transformer in each of the above cases may be replaced by a complex impedance. But since the secondary is tuned to the operating frequency only a pure resistance will be seen. The primary is also tuned, so the resultant load for the generator-resistance source is solely the reflected resistance, marked as R_3 in the Table and in Figure 23. Only in Case One is the load less than the primary resistance; in the other cases there is a definite overcoupling effect. In summary, the only noticeable bandwidth limiting will occur in Case One.

D. Signal Transmission at VLF

As discussed above, VLF signals have predictable propagation characteristics, with a dominant ground-wave transmission mode. They may be received reliably at long distances by aircraft, surface stations, and submerged vehicles. For these reasons present day use has been generally dominated by the military and scientific communities. High radiated power is the basic requirement for successful operation.

The entire VLF band from 10 to 30 kHz is only 20,000 Hertz wide. It is important to use this resource in the best manner possible, which means a tradeoff between the number of channels available and the bandwidth of each channel. Since the amount of information and the speed at which it is sent are determining factors in selecting the required bandwidth, it is important to consider all the factors involved.

In the discussion of VLF aerial systems it was pointed out that the aerial itself is usually a compromise in terms of the physical size which can be built. Due to top-loading and the small radiation resistance normally encountered the bandwidth is often less than 100 Hertz. (For the aerial discussed in the Impedance Matching section, the aerial bandwidth alone was about 38 Hz while the overall aerial system bandwidth was 76 Hz.) Although the overall system bandwidth may be increased (as discussed in the following section) there is usually a high price tag attached.

Prior to the 1950's most signalling at VLF was by CW (continuous wave) emission, also known as radio telegraphy. Reception was accomplished by human operators who transcribed the CW signals into letters and words. Because of this keying speeds were generally limited to the

range of 15 to 20 words-per-minute, and the small bandwidths required were well within the typical 100 Hz aerial system limitations. In fact, much effort was expended in trying to reduce the loss resistance in the system so that power could be more efficiently radiated. The corresponding reduction in bandwidth. [see Equations (1.a) and (2)] would merely reduce the available system response down to that compatible with the keying requirements.¹

It is important to examine the more common form of emission used in radio communications, especially those which enjoy wide usage in the High Frequency (HF) spectrum from 2 to 30 MHz, and determine their applicability to VLF signal transmission.

The normal voice or audio channel is considered to have a 3,000 Hz bandwidth requirement. Standard double-sideband Amplitude Modulation (AM) has two identical sidebands, so each station using AM would require at least a 6,000 Hz channel. This mode of emission may be eliminated from consideration since only three stations could operate in the entire VLF band, and with the aerial system discussed thus far the 100 Hertz bandwidth restriction would not permit operation.

Single-sideband (SSB) with or without carrier, can be considered to have only a 3,000 Hz bandwidth requirement. Although the number of operable channels could now be increased to six, the aerial bandwidth restriction would still not allow proper operation.

Narrow Band Frequency Modulation (NBFM) systems are usually considered to have roughly the same bandwidth as normal AM systems, when carrying an audio signal, while Wide Band Frequency Modulation (FM)

is by definition a system with a greater modulation index (and consequently greater bandwidth) than NBFM. Both of these systems may be eliminated from consideration.

The above systems (AM, SSB, NBFM, and FM) have been discussed using an audio signal. In the HF bands, it is common practice to use frequency multiplexing and place a number of Teletype channels in the place of one audio channel. The data rate of such a system is much greater than the original voice signal, and makes good use of a given 3,000 Hz bandwidth. It would be interesting to try this same approach at VLF, but once again the determining factor is the bandwidth of the aerial system.

Perhaps the most satisfying results may be obtained by starting with the major limitation, the aerial bandwidth, and seeing what type of system can best be used and still meet the restrictions. If 100 Hz is taken as the bandwidth for each channel, as many as 200 channels may be put in the VLF spectrum.

Since CW operation was the most common form of signalling prior to the 1950's, it is important to look at its operating characteristics in more detail. It is basically a form of Amplitude Modulation, where the modulation is set at 100 per cent; that is, the carrier is either full on or completely off. This is binary (two-state) keying in its simplest form.

Each letter and number is made up of from one to five parts or units. The basic unit is the "dot," a short duration "on" pulse. A "dash" is a longer pulse, equal in time duration to three consecutive dots. Spacing between dots and dashes is an "off" pulse (actually no pulse at all) equal in length to a dot. An "off" pulse equal in

length to a dash is used for spacing between letters. See Figure 24. The basic word has six characters, five letters and a space, plus two extra dots at the end of the word.¹⁸ The standard length word for determining signalling rates in the military is CODEZ, which is the equivalent of 60 dots long.

If a word consisting of five consecutive letter "e's" was to be sent it would require five dots for the "e's" alone and four dashes for the spaces between the letters, taking a total time equivalent to 17 dots. The numeral zero (Ø) is represented by five dashes, with a space of a dot between each dash, for a total time of 19 dots. When sending a word consisting of five zeros, a time corresponding to 107 dots would be required.

In using CW consisting of only letters and numerals (punctuation marks are usually six units long), a single word may range from 17 to 107 dots in length. The International Morse Code is arranged such that the more commonly used English letters are shorter in time than the less common letters, but even so, one word may be more than six times longer than another.

The bandwidth requirements for CW using International Morse Code can be expressed approximately as:¹⁸

$$BW_{cw} = \frac{1}{2} \text{ WPM} \quad \dots(72)$$

where BW_{cw} = bandwidth in Hertz

WPM = Morse Code words-per-minute

The standard word CODEZ has been used to determine Equation (72), so the expression is applicable to both English words and random "five letter code groups," since it represents an average word length of 60 dots. However, the "five letter code groups" (often used as a

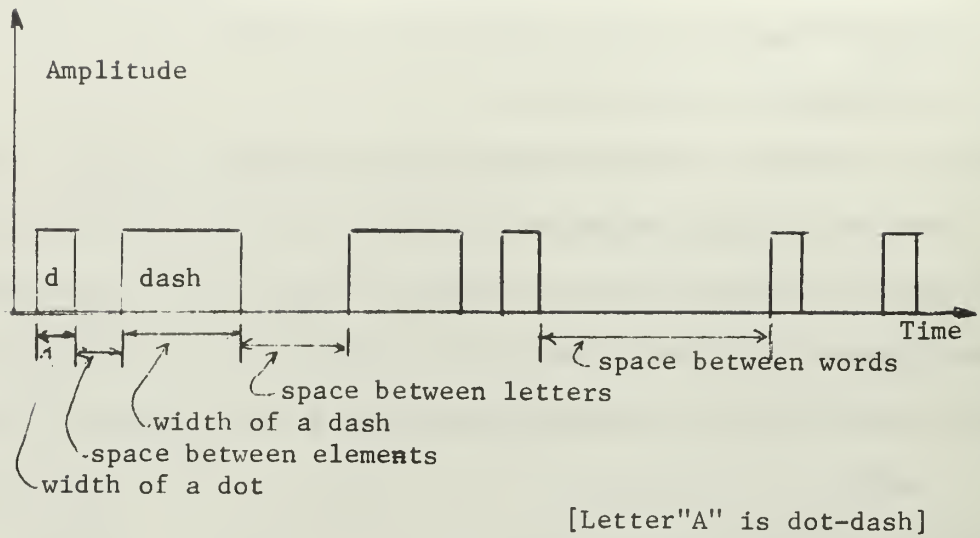


Figure 24. International Morse Code

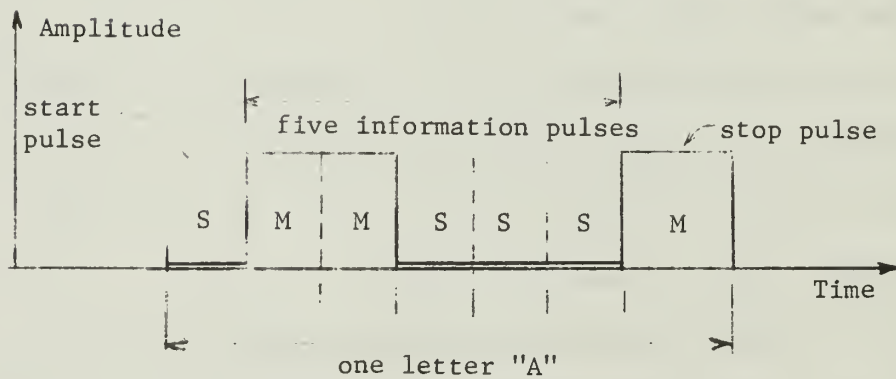


Figure 25. Teletype Character (Letter "A")

basic form of intelligence coding) will be random in terms of the letters used, and thus show more variation in length than a normal English text. The resulting wide range in sending time causes a loss of effectiveness in such a coding procedure.

In the last ten years machines have been developed which will "copy" CW transmissions, replacing the normal human operator since they are capable of accepting speeds which before only the most talented operator could copy, and with far fewer errors. Digital logic circuits are employed and once properly tuned the machine will produce an output printed on a normal Teletype page printer inserting carriage return and line-feed signals at the appropriate times. With a Boehme mechanical CW keyer at the transmitter CW rates at up to 60 words-per-minute may be used.

A signalling method in widespread use today is Teletype, where the common instruments employed are typewriter-like keyboards and printers. In this system each letter, numeral and punctuation mark are of equal length, so that any combination of five letters, numerals or punctuation marks will take exactly the same time to send. The basic system uses a seven unit character. The first is a "start" unit, the next five depend on the element to be sent, and the last is a "stop" unit.

Both Teletype and CW Morse code are basically binary signalling systems. In the first, however, each character always has seven basic units, where in telegraphy it may vary from one to six. The five "information" units in Teletype must always be sent, but since they are all of equal length, the arrangement of the five units does not effect the time required to send them, as is the case in CW. The

"dots" and "dashes" of telegraph sending are "on" signals, with "off" pulses used for separation. In Teletype the five information units are also distinguished by the difference of two states, but the states are not strictly limited to "on" and "off." The reference level may be set at the bottom, as shown in Figure 25, giving on and off pulses (called "mark" and "space" respectively), or it may be set to the upper limit. Either of these systems, using positive or negative-giving pulses, is known as "polar" keying. If the middle of the pulse is chosen for reference then the keying is called "bi-polar."

With five "information" units, each of which may be in either of two states, there are 2^5 or 32 possible combinations. The 26 letters of the English alphabet may be included, but there is not room for all of the numerals of the decimal system. To satisfy this requirement two additional characters are used: "Figures" and "Letters." The first shifts the keyboard and printer to what on the normal typewriter would be the upper case position. The characters used for letters in the lower case or "Letters" position may now represent numerals, punctuation marks, weather symbols, or special symbols such as a bell. If a "Letters" character is again transmitted a shift is made to lower case and alphabetic characters are once more sent.

Thus with seven-unit Teletype coding up to 62 different characters, each requiring the same time duration, may be sent.

In any binary system it is important to be able to properly recognize which of the two states is being received. With CW operation the two states usually chosen are on and off. Since reception is most often done by a human operator, the relative spacing between the lengths of dots and dashes can be varied somewhat and perfect copy still result.

Teletype operation, however, depends on the timing of the pulses, and the allowable variation from the proper timing is much less. Additionally, Teletype signals are decoded by machines, so the adaptability of a human operator is not available.

If the binary levels of zero and one are chosen, it is a simple matter to distinguish the two signals. When noise enters the system the basic reference level, if initially chosen at zero, will become instead the noise level. To counteract this a "threshold" may be chosen, say at $\frac{1}{2}$ unit, so that any pulse received which is greater in magnitude than $\frac{1}{2}$ will be considered as a signal of one unit; signals less than $\frac{1}{2}$ will be considered as zero level. Noise spikes of magnitude greater than $\frac{1}{2}$ may cause an error, but the average noise level will not. The proper choice of threshold level is not as simple as presented here, and quite a bit of work has been done on coding and levels, especially at VLF.¹⁹

Rather than a choice between two levels, improvement in the decision process could be realized if there were more accessory requirements. For example, a Teletype mark could be transmitted at one radio frequency and the space at a second frequency. Then a true mark would require a signal to appear at the proper mark frequency and no signal to appear at the space frequency. Detectors at the mark and space frequencies would employ the threshold logic described above.

Table V shows the four possible mark-space combinations in a noise-free environment. If the transmitter is properly operating Cases One and Three would never be received. The threshold detectors might produce such an output, but sophisticated circuitry would remove them, or else properly indicate an error. Cases Two and Four would be proper signals.

TABLE V

MARK-SPACE TRUTH TABLE

Case	Signal at		Comments
	Mark	Space	
1	0	0	Transmitter off, severe signal fading. Logic circuit would recognize as incorrect signal.
2	0	1	Space.
3	1	1	Incorrect signals, logic would recognize and indicate as an error.
4	1	0	Mark.

Error correcting codes and similar plans to improve accuracy have been proposed and are in use. But the problem at hand is to make use of two separate signals for Teletype signalling at VLF.

(It is seen that CW could be used with this arrangement, sending separate dots and dashes. But the very attributes of the Morse code, i.e., variation in character length, are a detriment here, especially in terms of selecting proper timing intervals.)

Two methods of generating separate mark and space signals for radio communications are commonly used. The first is Frequency Shift Keying (FSK), where the transmitter carrier is shifted between two discrete frequencies. Audio Frequency Shift Keying (AFSK) has the carrier transmitted continuously with two signals present in an audio sideband: one audio signal used for mark and the other for space. Where more than one Teletype channel is to be sent the AFSK method is generally employed, for here there may be several pairs of mark and space signals, all within a 3,000 Hz audio sideband. The carrier, in fact, need not be sent at all if a single sideband unit is used, and for elaborate systems

it is possible to transmit up to four independent sidebands from the same transmitter, each 3,000 Hertz wide, and each containing 16 or more separate Teletype channels.

In the VLF spectrum phase-continuous shifting of the main carrier is the most advantageous method of employing FSK.²⁰

Phase continuity is required to maintain a high level output and avoid serious transients in the antenna system, and in effect means that when shifting from one frequency to another both waveforms must be the same, i.e., both maximum or both passing through zero in the same direction. This may be achieved by using a single variable oscillator, switched at the signalling rate, or by switching the output between two separate oscillators. The difference between the mark and space signals depends on the system employed; at HF frequencies it is commonly 850 Hertz. A radio system meeting the phase-continuity requirements is actually using a form of Frequency Modulation (FM).

In simple terms, an FM system is initially at rest at some assigned frequency (carrier or center frequency). If a signal such as a sine wave is to be transmitted, then the radiated frequency will shift up from center frequency as the magnitude of the sine wave increases from zero, reaching its maximum deviation from the assigned carrier frequency when the sine wave is at its maximum value. As the magnitude of the sine wave decreases the carrier will be lowered in frequency until back at its assigned frequency. At this point the input sine wave will be at zero magnitude. The carrier will then be shifted down in frequency as the sine wave goes negative, finally returning to the center frequency at the end of one cycle. See Figure 26. The maximum deviation of the carrier from the center frequency is a function

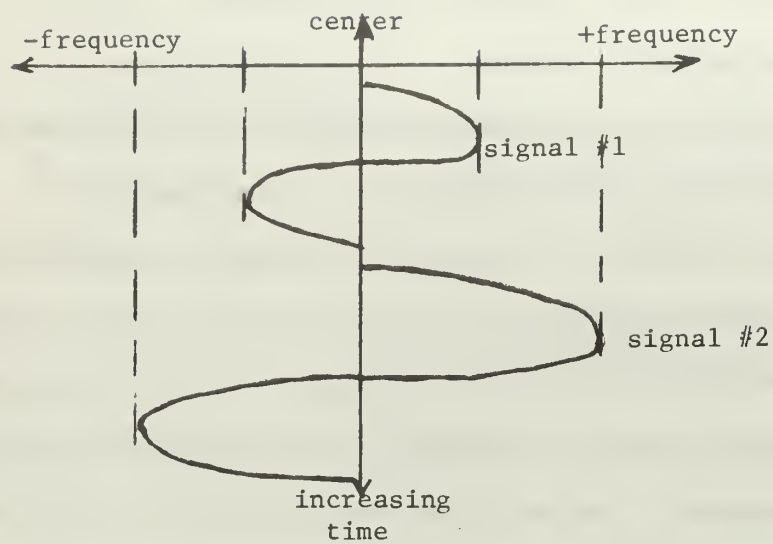
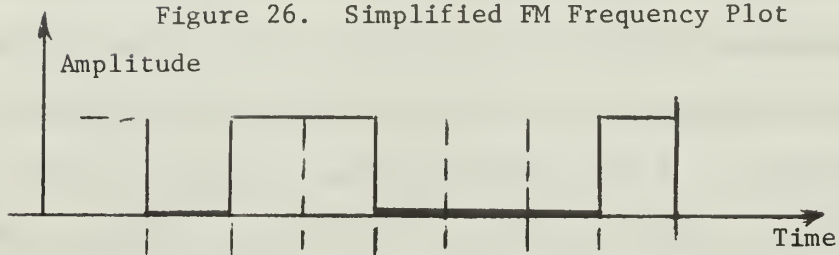
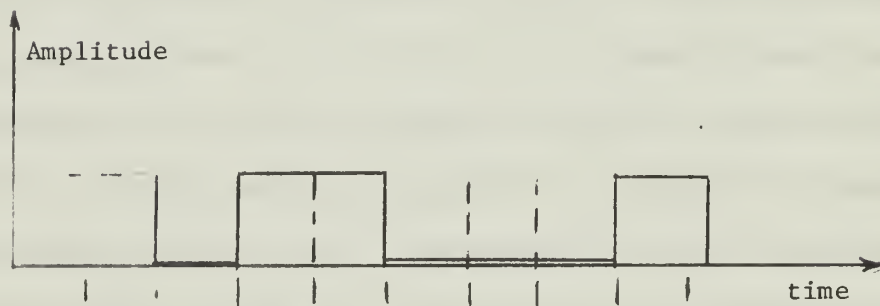


Figure 26. Simplified FM Frequency Plot



A. Equal time periods



B. Actual Teletype Signal

Figure 27. Theoretical and Actual Teletype Waveforms

of both the magnitude of the sine wave and the modulation index of the FM system.

The "modulation index" is defined as:

$$m = \frac{\Delta f}{f_s} \quad \dots(73)$$

where Δf = deviation of upper (lower) frequencies from the center frequency.

f_s = signalling frequency.

The maximum deviation allowed by the transmitter is a specified parameter, so the modulation index normally varies with the information signal. By definition Narrow Band FM has an index much less than $\frac{\pi}{2}$ while normal or wide band FM has an index equal to or greater than $\frac{\pi}{2}$.

For Teletype signals the carrier frequency is usually shifted upward for a mark and downward for a space, in both cases using the maximum allowed deviation. Since the shift is not instantaneous the signalling waveform may be "shaped" to reduce keying transients.

In Teletype operations it is common to speak in terms of a data rate in words-per-minute. For military usage, both 60 WPM and 100 WPM are common, with recent emphasis on the latter. The equations below are based on the normal word consisting of six characters (of seven elements each), five letters and a space. The elements per second are of most interest, however, and for this the term "baud" is used. A baud is the basic data or element rate, that is, elements per second.²¹

$$WPM = \left(\frac{\text{elements}}{\text{second}} \right) \left(\frac{1 \text{ character}}{7 \text{ elements}} \right) \left(\frac{1 \text{ word}}{6 \text{ characters}} \right) \left(\frac{60 \text{ seconds}}{\text{minute}} \right)$$

$$WPM = (1.43) \times \text{Baud} \quad \dots(74)$$

$$\text{Baud} = (0.7) \times WPM \quad \dots(75)$$

From Equation (75) 60 WPM Teletype has a baud rate of 42, so each identical pulse will have a time duration of 23.8 milliseconds, where time is the reciprocal of frequency. This is shown in Figure 27(A).

In practice the pulses are not of equal time duration. The stop pulse is made 1.42 times longer than the length of the start and information pulses, so the standard character requires 7.42 units of time. This means that each time unit must be approximately 22 milliseconds long and the stop pulse will be approximately 31 milliseconds long. The average length is still 23.8 milliseconds, but the shortest pulse present is of the most concern and sets the basic bandwidth requirements.

A signalling speed encountered where United States and allied military communications are concerned utilizes a 20 millisecond 7.42 unit code. This corresponds to 50 baud operation, and by Equation (79) has a data rate of approximately 67 WPM.¹⁷

Fourier analysis shows that an ideal square wave consists of an infinite number of sinusoids at various magnitudes. In the FM FSK method of transmission the signalling frequency must be known to properly determine the modulation index and frequency deviation [Equation (73)]. As a first approximation a sinusoid may be fitted to the square wave which has the same magnitude, zero crossings, and period. The resulting waveform then has a period of 40 milliseconds or a frequency of 25 Hz, as shown in Figure 28.

The signalling frequency of 25 Hz is a rough estimate at best, but with it an idea of bandwidth requirements may be determined.²²

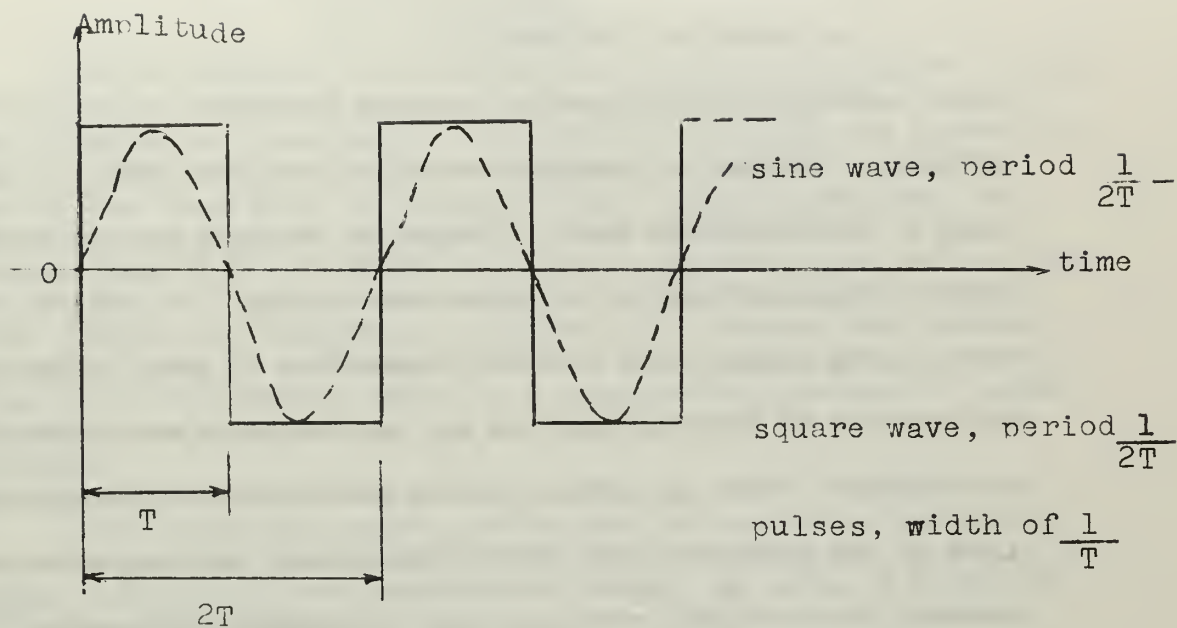


Figure 28. Pulse, Square-wave and Sine-wave
As Signalling Waveforms

$$BW = 2 (f_d + f_m) \quad \dots(76)$$

where BW = total bandwidth required

f_d = frequency deviation for mark or space

f_m = signalling frequency

Proper solution of this equation requires knowledge of the allowed deviation. Studies of frequency deviation have been made through a study of the modulation index. Indices of one-half and one have been found particularly useful for square wave keying. An index of one-half uses all the signal power from the transmitter to carry information, but there is no discrete power at any one frequency and synchronization is difficult. When an index of one is used there are discrete spectral lines at the upper and lower shift frequencies, but they also take one-half of the signal power and carry no message information.²⁰

In actual message transmission random pulses rather than square wave keying will be useful. In this case the spectral density will vary from those described above.²³ Here the choice of a modulation index of one for phase continuous binary keying appears to be optimum.

The application of FM to high power VLF transmitters has been successfully accomplished only within the last 20 years.²⁴ Early studies in keying low frequency transmitters using reactance tubes were carried out at Westinghouse Corporation in early 1950. An experimental FSK system using a baud rate of 50 with a modulation index of one was operated between San Diego, California and Leesburg, Virginia with a radiated power of one kilowatt in the early 1960's.²¹

One difficulty in using FSK at VLF is the small frequency shift (25 Hz for a modulation index of one for the 67 WPM discussion above) as opposed to the more common 850 Hz shift in the HF region.

Such small shifts can be successfully detected as reported in one study which used only 18 Hz for 100 WPM operation.²⁵

E. Broadbanding

Narrow bandwidth of VLF aerials is the major limitation to high speed information transmission. The impedance matching and transformer circuits have been shown to be practically lossless, and since the bandwidth (and Q) of the aerial is directly dependent upon the resistance in the circuit, an increase in resistance will increase the bandwidth. At the same time, however, there is a corresponding decrease in system efficiency.

A direct attack on the problem would be to place a fixed, high wattage resistance across the parallel circuit, as shown in Figure 29. The new resistance will lower the circuit Q and increase losses. The variable inductance may be used to vary the influence of the resistor on the circuit, giving the effect of a variable resistance.

In practice such a broadbanding resistor would be of comparatively high value and with the series inductor set at its full value have only a slight effect on the original antenna circuit. Since the antenna circuit in general would already have been designed, the best position would be between the aerial coupling unit (helix system) and transmission line impedance matching network. Then the latter network could be slightly retuned to maintain a proper input impedance. See Appendix A.

A second approach is more sophisticated and will not introduce as much loss (in theory no loss at all!) but calls for special devices. The idea is to automatically tune the aerial system to resonance in synchronism with the information signal. Under normal conditions the aerial has a very sharp response curve with 3 db points less than 50 Hertz

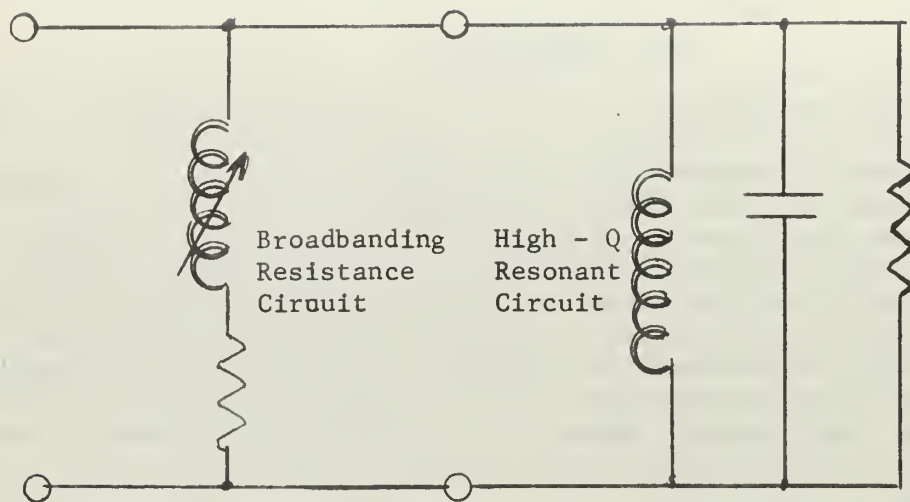


Figure 29. Additional Resistance For More Bandwidth

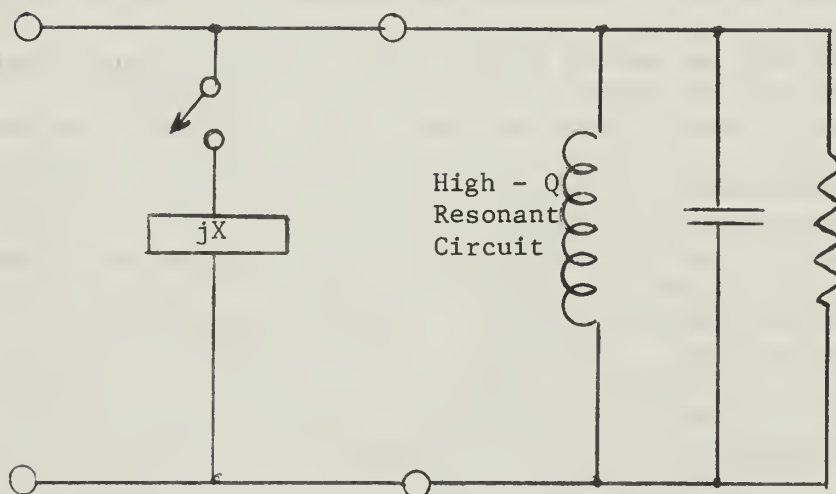


Figure 30. Switchable Reactance For Broadbanding

either side of the center frequency. If a bandwidth of 150 Hertz was desired, and FSK was used, then in theory the antenna could first be tuned for operation 75 Hz below the center frequency; then with a new reactance in the circuit be retuned to resonance 75 Hz above the center frequency. If the new reactance was switched at the same rate as the FSK, then at both mark and space frequencies the aerial would be resonant.

Figure 30 shows this schematically, using a reactance jX in parallel with the tuned circuit. At the lower frequency f_1 the basic circuit components are used; at the high end (f_2) the new reactance is added and it is tuned for circuit resonance at this frequency.

In 1954 Jacob and Brauch put forth the idea of using a saturable reactor for the switched tuning element.²⁶ An experimental model of such a device was found to dissipate about 20 KW when full frequency shift was employed using a 500 KW transmitter. Special modulation equipment was required to obtain the desired results, and the saturable reactor itself measured over 1,400 cubic feet and weighed about 23 tons. Operation with Teletype FSK was successful using a 100 Hertz shift at 19 kHz.

Wolff reported in 1957 on a variation of the method above, using a variable capacitance as the switched reactance. Vacuum tubes were keyed with the Teletype signal and effectively varied the reactance. This method was applied to a 10 KW transmitter operating at 28.5 kHz using a shift of 100 Hz. However, modulator tubes for high power (above 10 KW) VLF operation were not available.²⁷

More recently the problem of transients in the tuning arrangements above have been considered. Galejs points out that in an LC

resonant circuit the energy is alternately stored in the inductive and then the capacitive elements. If one of the elements (or part of that element) is switched out of the circuit at the instant it contains all the energy available, there will be no transients. The element may then be switched back into the circuit when the other reactance has again reached a zero energy level. Although the author discusses FSK applications at VLF and variation in parameter values, switching timing and the switches themselves, there appear to be many practical problems which would require a great deal of study.^{28, 29}

The ideas expressed by Wolff and Jacob generated a great deal of thought in the area of reactance variation for increasing bandwidths in linear circuits. The use of principles normally associated with servomechanisms and magnetic devices were applied to the problem by Johannessen in 1964.³⁰ He suggested the use of two non-linear inductors connected in series with the VLF aerial tuning coil. The average inductance of these devices is caused to vary in accordance with the keying signal, through the use of a feedback signal derived from the phase difference between the antenna current and transmitter voltage. No computations regarding the size of the non-linear inductors are given, but additional equipment for phase detection and inductor control are required. The author states that a small-signal transient analysis shows the system to be limited to a new total bandwidth equal to one-fourth the bandwidth of the power amplifier which drives the inductors. This, however, should not pose any real problems at the VLF frequencies where the system bandwidths are relatively small.

The most promising idea for increasing aerial bandwidth was presented by Zverev and Blinchikoff in 1964.³¹ Here the aerial radiation

resistance is considered as a resistive load and the transmitter as a source with series resistance. The desired bandwidth is determined as part of an overall frequency response and by network synthesis a circuit having the desired Butterworth or Chebyshev response is designed. The aerial reactance is then included in the analysis and combined with additional components to complete the bandpass filter network. The article gives numeric tables for circuit design including response time, ripple and bandwidth. When a two-pole Chebyshev filter is designed (which is recommended as the most economical) the resulting two resonant peaks may be adjusted to coincide with the mark and space frequencies for FSK Teletype transmission.

The example filter included by the authors was for pulse or square wave modulation and was built as a simple Tee network. Although impedance transformation was not a primary concern in this case, it could perhaps be included in a more thorough analysis, or else a separate wideband impedance matching network could be added.

When a VLF aerial is connected to a transmitter an additional resistance will be placed in the circuit since the power amplifier may be represented as a zero-impedance source in series with its internal resistance. Thus there will be an increase in bandwidth. Since power amplifiers for VLF are usually operated Class C, the exact value for the generator resistance is difficult to determine. It has been suggested that as a rough guideline the bandwidth of the antenna system can be increased by an amount found by multiplying the present bandwidth by the reciprocal of the Class C amplifier efficiency. If this procedure proves correct the tubes could be operated at lower efficiencies and the increased bandwidth achieved. This method is

expensive in terms of power dissipation and overall system efficiency, but an increase of approximately 12% can be achieved if the amplifiers operate at their nominal 80% efficiency.

In summary, some form of broadbanding for the normal VLF antenna system is required if high speed (wide bandwidth) information transmission is desired. This may be done by brute force -- the introduction of additional resistance into the circuit. Less power will be lost if a variable reactance is switched into the aerial circuit synchronized to the signalling information to tune the aerial to the separate mark and space frequencies. Transients are a problem here. The most potentially beneficial broadbanding method is to synthesize a bandpass filter having the desired frequency response. Regardless of which method is used, an increase in bandwidth of the overall system (but not the aerial itself) will be provided by the source resistance of the power amplifier tubes.

III. SYSTEM USED AT NORTHWEST CAPE, AUSTRALIA

In the Basic Principles section VLF aerials, matching and coupling networks, signalling methods and bandwidth widening techniques were discussed. For any particular VLF installation all of these areas will be important, but certain areas will vary among installations. In the writing of a computer program for VLF systems numerical values must be used, at least in the checkout phase of the program.

Rather extensive data on existing U. S. Navy VLF stations, as of 1963, has been compiled.¹ However, the installation at Northwest Cape, Australia was under actual construction during the time this thesis was being written, and could be expected to incorporate the latest techniques in the VLF art. Additionally, William E. Norris, Professor of Electrical Engineering, Naval Postgraduate School, was assigned to the installation and could provide up-to-date information. Field engineers were making minor corrections and numerous measurements daily, so a great quantity of detailed information was available. For these reasons, the Northwest Cape installation was chosen as the model for the computer program.

The transmitter-antenna system was designed to operate in the frequency range from 15.5 kHz to 30 kHz, with a radiated power of 1,000 KW. Major signalling is by 50 baud Teletype, using FSK with a shift of 25 Hz and a modulation index of one. CW operation would be available on an emergency basis. The assigned operating frequency is 15.5 kHz.

Table VI shows the major system parameters of the installation, and Figures 32 through 37 show the general schematics of the various units.

TABLE VI

DESIGN PARAMETERS FOR NORTHWEST CAPE, AUSTRALIA

General	Operating Frequency	15.5 kHz
	Radiated Power	1,000 KW
Aerial	Vertical monopole, with top-hat loading	
	Effective height	628 feet
	Required efficiency	50%
	Static Capacitance	0.164 μ fd
	Downlead inductance	139.0 μ h
	Radiation resistance	0.154 ohms
	Loss resistance	0.154 ohms
	Self-resonance frequency	33.3 kHz
	Aerial bandwidth	38.125 Hz
	Bandwidth (with loss)	76.250 Hz
	Antenna current (approx.)	2550 amps
Helix	Tuning Variometer	484 μ h
	Coupling Variometer	20 μ h
	Input impedance (at resonance)	12.5 ohms
Bandwidth	Resistor	33.25 ohms
Resistor	Maximum dissipation	500 KW
	Series Variometer tuning	200 - 800 μ h

TABLE VI (continued)

Tee	Input impedance	20.0 ohms
	Output impedance	12.5 ohms
	Leg One Inductor	25 - 275 μ h
	Leg Two Capacitor	.06 - .6 μ fd
	Leg Three Inductor	50 - 300 μ h
Transformers	Output impedance	20 ohms
	Primary winding	430 μ h
	Primary capacitor	0.25 μ fd
	Secondary inductance and capacitor settings vary with number of units being used.	
	One unit Inductance	71.5 μ h
	Capacitance	1.475 μ fd
	k	0.522
	Two units Inductance	49.0 μ h
	Capacitance	1.076 μ fd
	k	0.474
	Three units Inductance	35.3 μ h
	Capacitance	0.996 μ fd
	k	0.444
	Four units Inductance	27.0 μ h
	Capacitance	0.976 μ fd
	k	0.508
Power Amplifiers	Four each AN/FRT-67 power amplifiers rated at (each)	500 KW
	Desired plate-to-plate load	420 ohms
Signalling	Teletype	50 baud
	FSK, modulation index	1.0
	Required minimum bandwidth	100 Hz
	CW for emergency use	

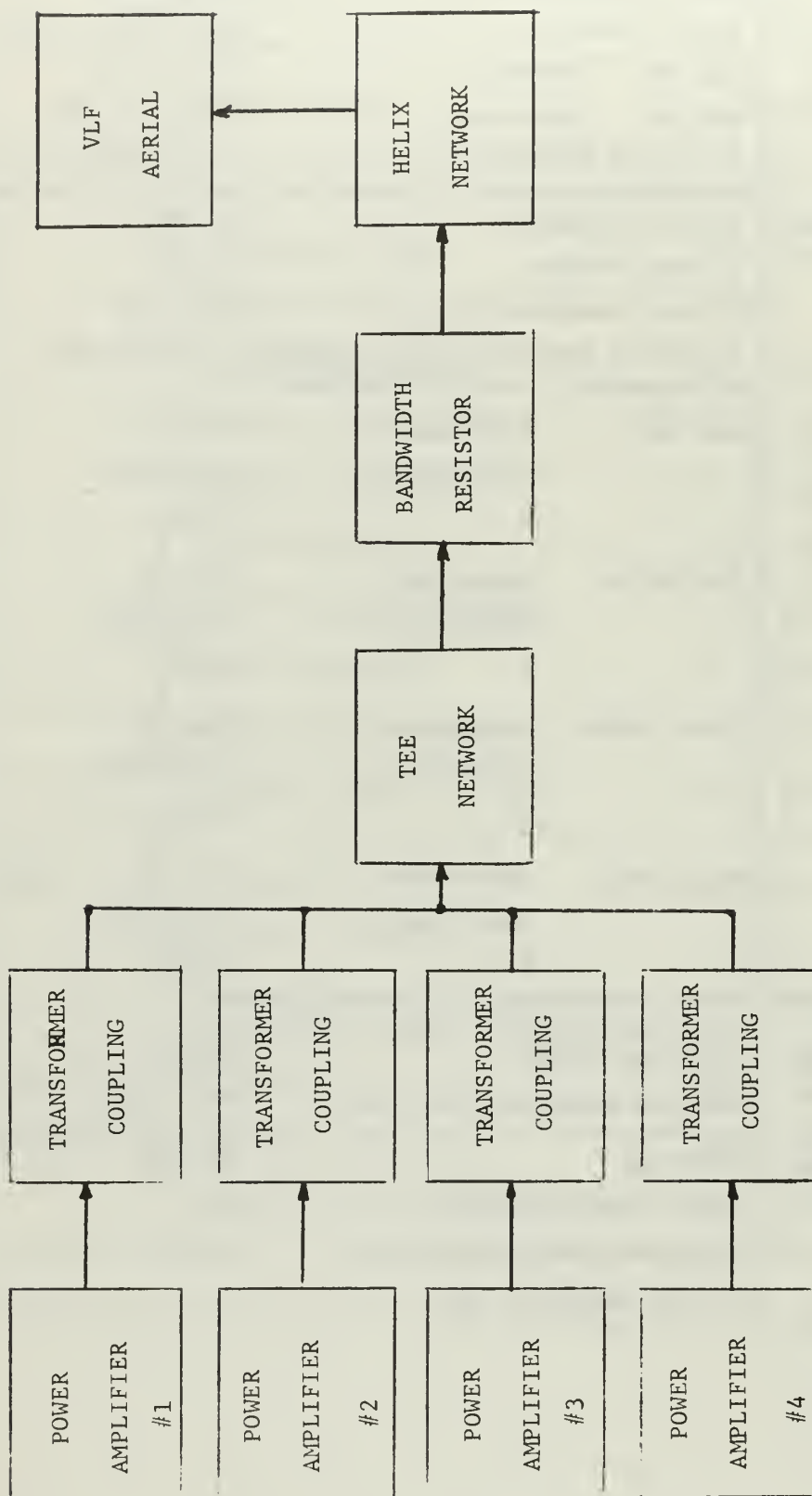


Figure 31. Block Diagram of Northwest Cape Installation

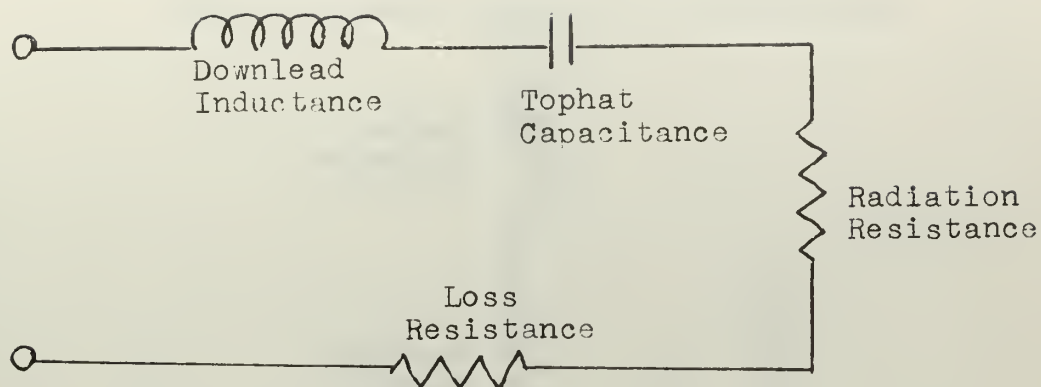


Figure 32. Aerial System

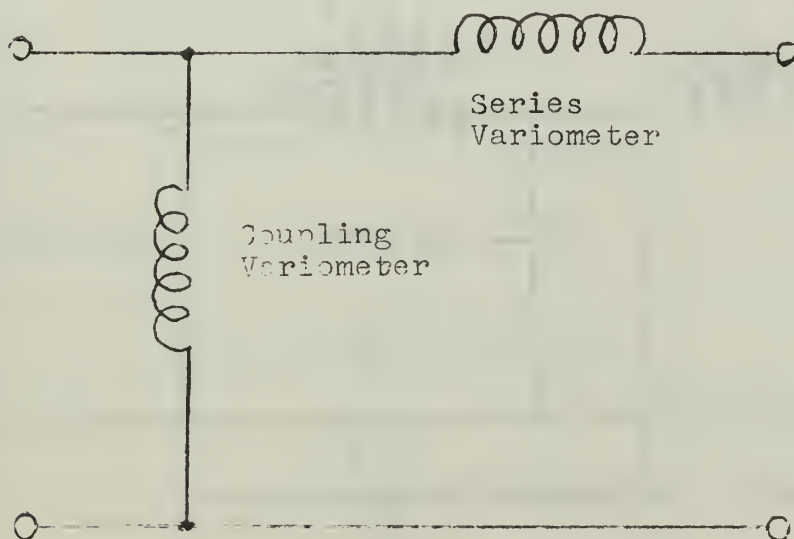


Figure 33. Helix Coupling Network

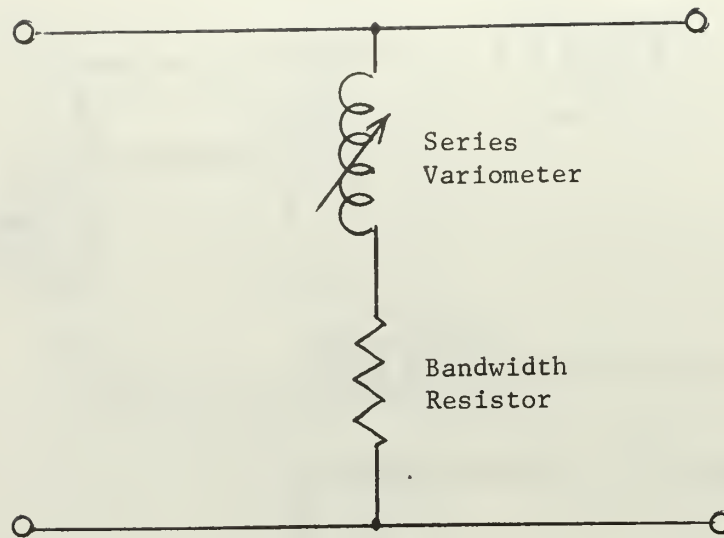


Figure 34. Bandwidth Resistor Network

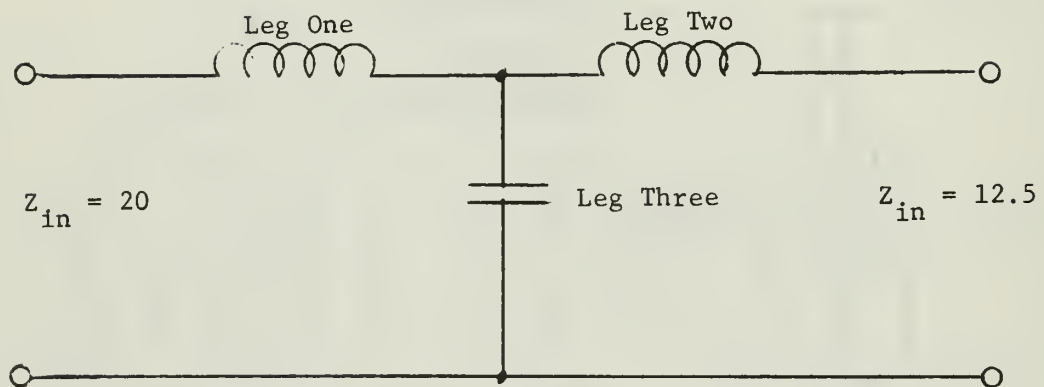
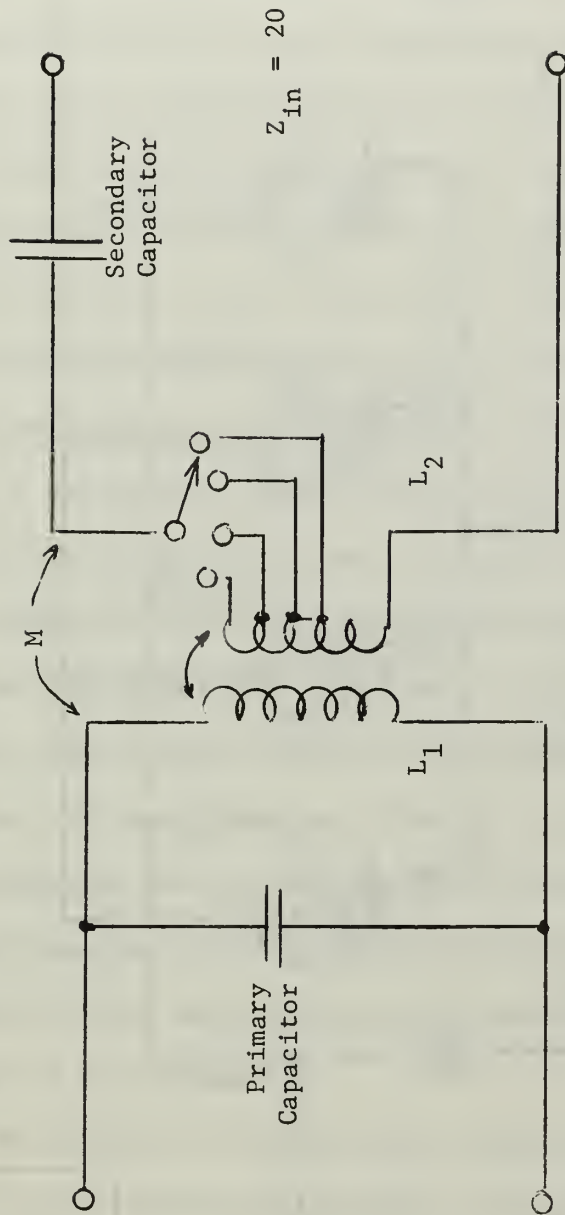


Figure 35. Tee Impedance Matching Network



Note: Transformer secondary varies with number of power amplifiers on the line.

Figure 36. Transformer Coupling

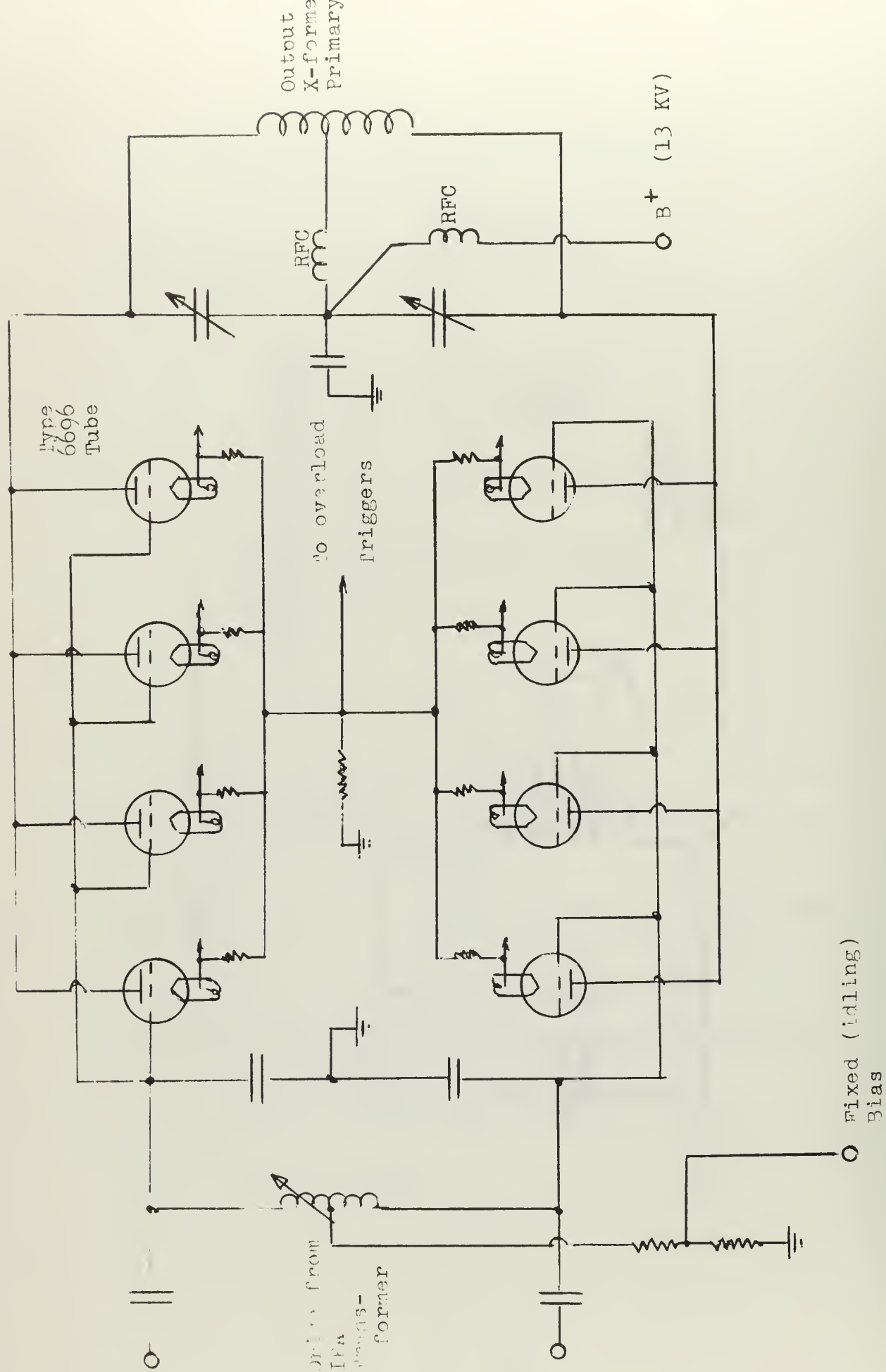


Figure 37. AN/FRT-67 Power Amplifiers

IV. COMPUTER PROGRAM

A. Outline

A program written for a high speed digital computer can be made to carry out simple tasks in an extremely short time. By combining a number of simple steps a more complicated operation may be performed. When using a specialized program for aid in designing a VLF antenna system some basic assumptions are made and the various parameter values may be permuted to observe the effect on the system.

The computer program written for this thesis (VLFANT) used the installation at Northwest Cape, Australia for the basic model. Thus the output or "results" apply only to this particular facility. However, VLFANT is sufficiently general that component values may be rapidly changed and the network may be modified with relative ease. In fact, a number of existing antenna systems can be run with this program by merely modifying aerial parameter values.

VLFANT is written in FORTRAN IV language for use on an IBM System/360 high speed digital computer. Full use is made of complex variables. The circuit under study is broken into five major sections: the aerial, the helix matching circuit, the bandwidth resistor circuit, the Tee matching circuit, and the power amplifiers-transformers coupling circuits. Each of the major circuits is put into a separate subprogram so that modifications may be made without effecting the remainder of the program.

In addition to the five Major Subprograms above, the Main program acts as the control section. It "calls" the Major and Minor Subprograms (discussed on the next page) and by making simple changes in Main the program output may be varied to give the designer precisely

what he wants each time the program is run. Also, the entire program except for Main may be put into "object Deck Format" which means the computer cards are changed from their original FORTRAN IV language into machine language. Then when the complete program is run only the Main program needs to be "compiled" (changed into machine language) yielding an important savings in computer time.

Six Minor Subprograms are included in VLFANT. These sections operate on the major circuit sections by putting them into the network analysis "ABCD" matrices, determining network response, variation in circuit Q, currents, voltages, power and phase relationships throughout the networks as a function of frequency. This data may then be displayed in a number of ways, including graphically from the standard paper printer unit. Detailed descriptions of each of these sections are given below.

Seven Accessory Subprograms are included. They are used by the subprograms above to perform repetitive mathematical manipulations, supply tuning limits for variable components, perform operations on matrices, and plot output data generated by other subprograms. They are described in detail later in this section.

For flexibility variable names in VLFANT were chosen to match normal circuit theory as closely as possible within the limits of the FORTRAN IV language. A great emphasis was placed on indexing these variables so that new circuits could be substituted without creating numerous program corrections. Figure 38 shows with block diagrams the basic designation of the antenna system variables. Note that each of the five major circuits is numbered so that all measurements and parameter values dealing with a specific section will have an index number

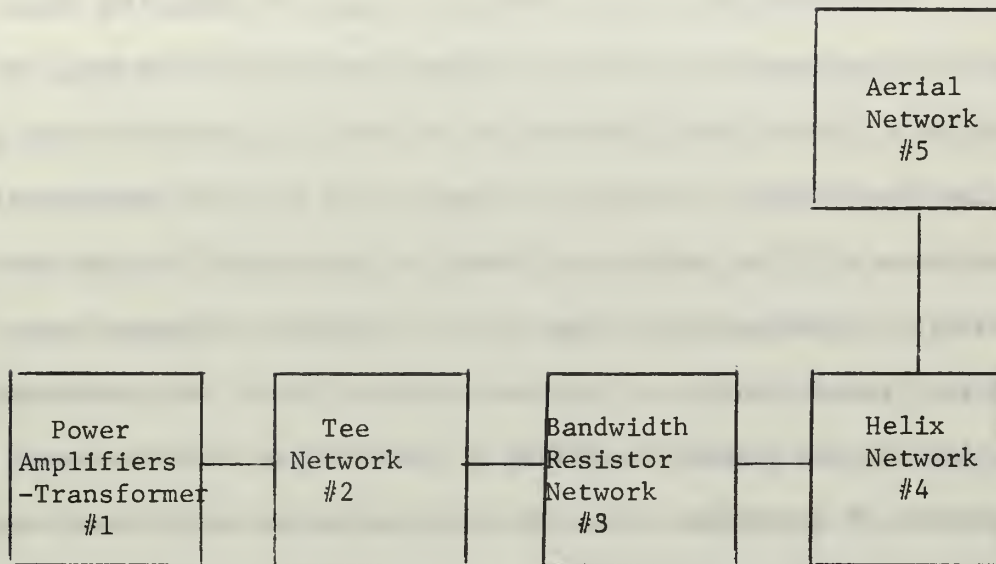


Figure 38. Major Circuit Sections

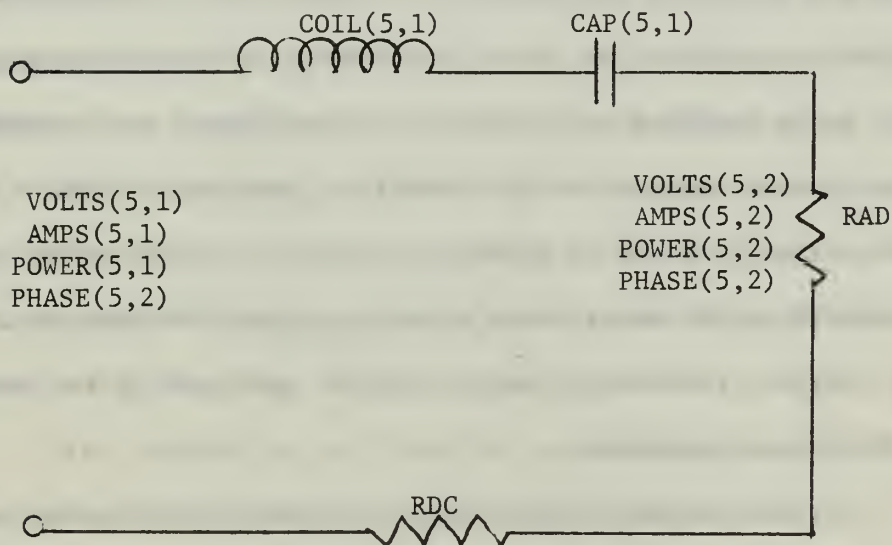


Figure 39. Aerial Network

corresponding to that block. Each block is further divided into an input and output designation.

As an example of the indexing, Figure 39 shows the Aerial circuit with components and circuit parameters indicated as they are used in VLFANT. Since this block number is five, all variables have a "5" as the first index. Currents, voltages, and so forth dealing with the input have a "1" as the second index; at the output (in this case the radiation resistance) the index is "2." Reactive elements are numbered sequentially, and reactance values follow the same notation. [XL(5,1) is the complex impedance of COIL(5,1) at the designated frequency of operation, i.e., $j\omega L$.] Resistances are the only exception to the indexing terminology; since there are only three in the entire antenna system they are given descriptive names.

A certain amount of duplication occurs with this indexing system. At the connection between the Tee network and Bandwidth resistor blocks, for example, VOLTS(2,2) and VOLTS(3,1) are equal, and so are AMPS(2,2) and AMPS(3,1). Flexibility is maintained, since in one study it may be of interest to allow different power levels to be radiated by the aerial and determine the voltage and current levels required at the bandwidth resistor, in which case the Tee network is not of immediate concern. Or the effect of the Tee network may be under study assuming a fixed voltage at its input and a constant resistance load, in which case none of the other circuit blocks are required.

Further network manipulation is possible since the bandwidth resistor may be removed and a transmission line inserted, or the Tee network might be replaced by a Pi network. Providing the same notation is followed, these changes may be readily accomplished.

A great deal of use was made of "COMMON" statements throughout the program. These statements allow a block of storage in the memory cells to be used in common by many subprograms, substantially reducing the overall storage space required. Many terms are common to the majority of subprograms, such as VOLTS(a,b) and ZTOTAL(a,b), and via Common they are always available when needed. Additionally, variables in Common do not need to be handled through a calling statement when using a particular subprogram, so simplicity in use is achieved.

General operation of VLFANT is divided into two major areas: the first based on an impedance analysis and the second on a voltage-current analysis.

Beginning with the given aerial component values and radiated power, the entire system is analyzed to find the impedance values at the input to each of the sections at the specified operating frequency. Impedance values for the helix and Tee networks are already specified, so the inductance and capacitance settings required are determined. The plate-to-plate resistances for one, two, three, and four power amplifiers are the end result of this part of the program.

When determining values for variable elements a notice is given if the required setting is outside the tuning range. Computation continues with the computed value, however, so that later modifications of the tuning range may be made if desired.

With values for all components known, the program then uses the radiated power and radiation resistance to determine the "load" voltage and current. Through the use of "ABCD" matrices the corresponding voltages, currents, power and phase relations are determined

for each network working from the aerial to the power amplifiers. Impedances using Ohm's Law are also computed, as a check on the values previously determined.

At this point the frequency may be varied symmetrically on either side of the operating frequency by using subprogram DELTA. Impedance variations are determined for each circuit block, as are voltage, current and power levels, based on the plate voltage for the power amplifiers determined above being considered constant. The above data is presented in tabular form; it may also be graphed by calling the appropriate subprogram.

B. Major Subprograms

MAIN:

This is the major control section for VLFANT. All components are generally defined here: values for all inductors and capacitors, resistances, radiated power, desired impedance levels (such as at input to helix, at both input and output of the impedance matching network, power amplifier plate-to-plate, and bandwidth resistor), tuning ranges for all variable components, breakdown voltage levels, and so forth. Additionally all subprograms are called from MAIN, so just how the program is used can be determined here.

Other parameters are also defined, such as the operating frequency, the number of steps of each side of center to be taken when the frequency response is run, the size of each step, whether or not the bandwidth resistor is to be used in the analysis, and so forth.

Once the overall program is set up for a particular antenna system many parameters will have been roughly determined. For example, the tuning ranges for the reactances in the Tee network can be determined by hand, while the precise setting will be done by the computer. Then a simplification is possible by putting these "constants" into the BLOCK DATA program described below. This leaves MAIN free to carry out its main function: that of controlling the overall program.

An example of one MAIN program is included in Appendix B.

PRINT:

This subprogram supplies the first part of the computer program output. It prints the designated center frequency and desired radiated power. For the aerial the predetermined radiation and loss resistances and top-hat capacitance and down-lead inductance are presented. In the

bandwidth resistance circuit the value and maximum power dissipation of the resistor are printed as well as the tuning range of the variable inductor. Minimum and maximum values for the coils and capacitors in the Tee network are then printed. For the toroidal transformers the primary inductance is given, and then the coupling coefficient and secondary inductance of each transformer when used alone or as a part of a two, three, or four unit combination.

AERIAL:

This subprogram is concerned only with the aerial system, with the radiation resistance considered as the output parameter or load. The down-lead inductance and top-hat capacitance are the reactive elements, the radiation and loss resistances completing the circuit. All values are given from the initial conditions specified in the main program. The aerial self-resonance frequency, the "Q" and bandwidth (using only the radiation resistance) and the efficiency are computed and printed out. With a desired radiated power (from the main program) the required current is found as are the voltage across the radiation resistance and the "top-hat" and "base" voltages, those which appear across the reactive elements. The voltage across and current through the radiation resistance, VOLTS(5,2) and AMPS(5,2) are used as references for later voltage-current manipulations. The "output" of this program is the impedance seen at the terminals, ZTOTAL(5,1).

See Figure 39 for the circuit and terms used in this subprogram.

HELIX:

This subprogram uses the impedance of the aerial system as its load and ZIN as the desired impedance at its output terminals. The

program may use either of two methods to determine the values for the tuning and series variometers.

Method One considers the entire helix coil as the inductance used to resonate the aerial circuit [cancelling out the reactive part of $Z_{TOTAL}(5,1)$] and then finds the tap point to give a resistive load of Z_{IN} .

Method Two uses an analytical expression where the coil is tapped so that the input impedance will be purely resistive with a magnitude equal to Z_{IN} . Either method may be selected from the main program; the values for the series and tuning variometers are given in printed form, and the "result" is $Z_{TOTAL}(4,1)$.

See Figure 40 for the circuit and terms used in this subprogram.

TEE:

Values for the legs of the Tee network are chosen using the principle of a quarter wave transmission line, that is, the square root of the product of Z_{IN} and Z_{OUT} . The legs are numbered in accordance with Figure 35. Settings for the legs are easily determined.

Following determination of component values the tuning ranges for each component is checked to see if any out-of-range values have been selected, and, if so, the printout indicates whether the tuning is high or low and the value of the limit which has been exceeded.

Next the completed network is connected with the helix-aerial combination as a load, and the input impedance $Z_{TOTAL}(2,1)$ computed.

See Figure 41 for the circuit and terms used in this subprogram.

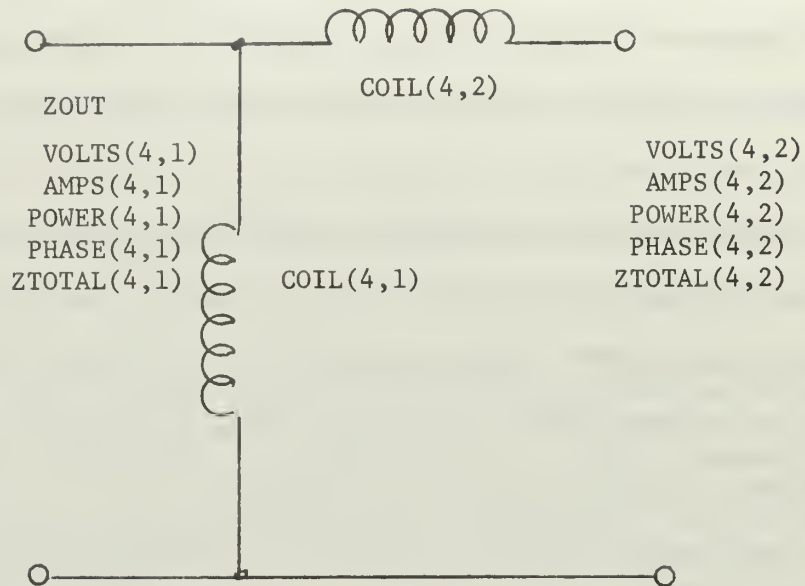


Figure 40. Helix Network

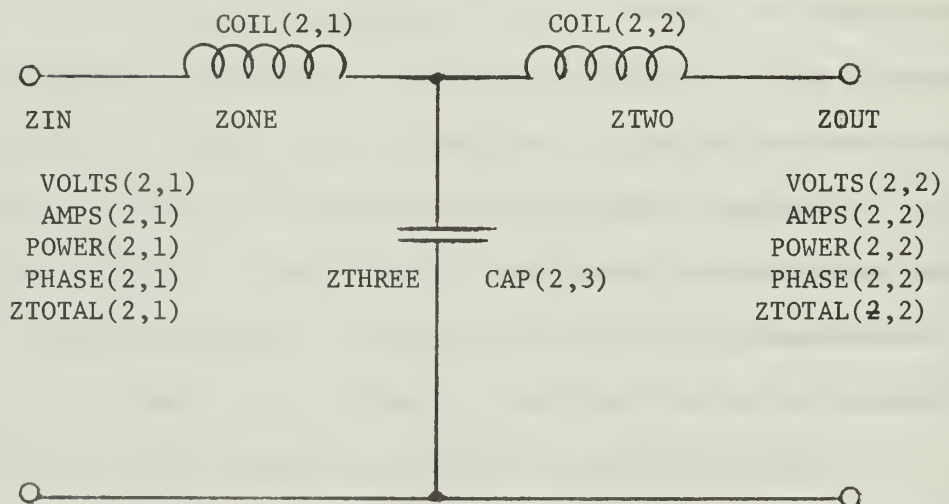


Figure 41. Tee Network

TANK:

This subprogram computes the plate-to-plate impedance for the power amplifier tubes using one, two, three, and four separate power amplifiers.

For a single power amplifier the impedance seen at the input to the Tee network is used as the load. Combined with the transformer, a single complex series impedance is computed. This is transformed to a parallel impedance, and the primary capacitive reactance added. The resulting impedance is that seen plate-to-plate.

When two or more amplifier units are used, it is necessary to determine the effect of the modified load as seen by each unit. Using the procedure discussed in the theory section, the primary impedance of each transformer is found for the various combinations. As above when using only one unit, a value for the plate-to-plate impedance is determined.

The printout shows the inductance value of the transformer secondary and mutual inductances, as well as equivalent primary impedance and resulting plate-to-plate load for use of one, two, three, and four power amplifiers.

See Figure 42 for the circuit and terms used in this subprogram.

RESIST:

This subprogram is used to determine the effect on the "Q" of the antenna system of the resonant frequency as the coupling coil is set at its high and low values. The resulting minimum and maximum "Q" are then printed out. Provisions are made to use the subprogram with an arbitrarily selected value for the coil; the resultant "Q" is computed and sent to the main program.

See Figure 43 for the circuit and terms used in this subprogram.

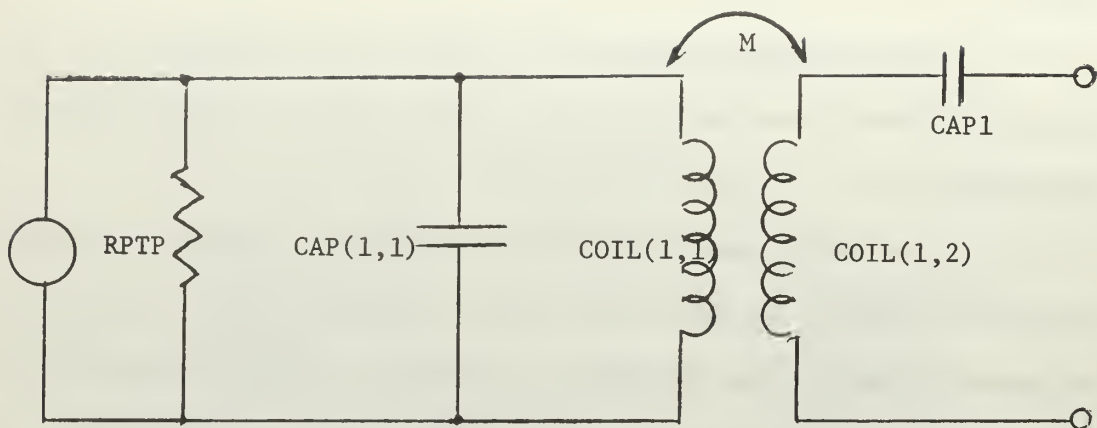


Figure 42. Power Amplifier/Transformer Network

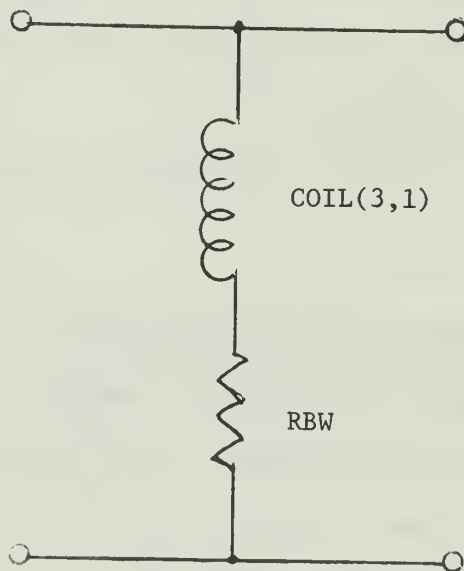


Figure 43. Bandwidth Resistor Network

C. Minor Subprograms

MATRIX:

Four terminal networks may be described by using complex two-by-two "ABCD" matrices, where the input voltage and current are found by multiplying the output terminal voltage and current by the ABCD matrix. If several networks are cascaded, then the input voltage and current parameters of the overall network may be found by multiplying the load voltage and current by the individual network ABCD matrices in sequence. If a particular network is removed from the overall circuit, then by merely leaving out its matrix the circuit may be re-analyzed.

In the Matrix subprogram each section of the antenna network is described in terms of its ABCD matrix. Individual matrices are written for one, two, three, and four power amplifier transformers. Values for all components are either given initially or computed in the subprograms described above.

Two matrices are developed for each section of the network if required, so that either set of terminals may be used for the input or output. In the aerial matrix, the radiation resistance is considered as the "load" or output impedance.

Frequency is the major variable in this subprogram and each matrix can be labelled and printed out if desired; the results are always returned to the main program.

DELTA:

This subprogram is used to determine the impedance of the various parts of the antenna system as a function of frequency. Component values are those computed at the center frequency. Deviations

from the center frequency are made equally both above and below; the number of steps (up to 240) and the increments of each step are determined by the user in the main program. Impedances at the aerial, helix, bandwidth resistor and Tee network are found at each frequency and put into arrays. Either of the two configurations for the helix matching systems may be used at the will of the user. Although values for the bandwidth resistor connected to the helix are computed, the user may choose to compute the Tee network response by considering the resistor as removed from the circuit.

In the TANK subprogram values were found for the secondary capacitor which would give a pure resistance load to the power transformer at resonance. In this subprogram these predetermined settings are used when two, three, or four units are put on the line. Then the plate-to-plate impedance is determined as a function of frequency when any combination of power amplifiers is used. These values are also put into array form in the subprogram.

An additional impedance array is computed and sent to the main program, but is not available for printed output in the subprogram. This is the sum of the aerial impedance and the reactance of the series variometer of the helix circuit. Defined as ZTOWR in the program, it will be used later to determine "antenna" current.

Output from this subprogram may be used in several ways. The impedance arrays, frequency array, and normalized frequency array (where the center frequency is set equal to zero) are all sent to the main program for further use. The printout of results is in tabular form: frequency and the network impedances in one table, and frequency and the transformer results in a second table. These printed results

may be omitted entirely, both used, or either one used at the discretion of the user.

QVARY:

This subprogram determines the variation of the aerial as a function of frequency over the VLF band from 10 to 30 kHz, in 500 Hz increments. First the Q and bandwidth (in Hz) for the aerial alone are computed. Then the loss resistance is included and the Q and bandwidth again computed under this "loaded" condition. The frequency and two pairs of computations are put into array form and returned to the main program.

It should be noted that the radiation resistance and reactive elements of the aerial used in this subprogram are those used in the main program. They are generally computed or measured at the frequency where operation is contemplated, and will vary with frequency, but are assumed constant here for purposes of examination over the VLF band.

The results may be printed in tabular form or suppressed if so desired by the user.

ANTAMP:

This subprogram will determine the change in various currents in the antenna system as a function of frequency. For use here, the voltage on the plates of the power amplifier tubes when full rated power is being radiated is used as a reference. (The particular voltage selected will depend upon whether one, two, three, or four units are on the line.) It is assumed here that the voltage will remain constant regardless of the frequency, a condition which is not in fact true, but may be logically made. (See the theory section under Transformer Coupling.)

The frequency is allowed to deviate equally both above and below the center frequency; the number of steps and the increments are those chosen when subprogram DELTA was called.

At each frequency, the current drawn from the power amplifier tubes is determined by dividing the plate voltage by the transformer impedance determined in the DELTA subprogram array for the corresponding frequency. The MATRIX subprogram now is used, at the chosen frequency, to compute the voltage at the output terminals of the transformers; this is divided by the impedance presented by the Tee network. At the helix network the voltage at its input terminals is divided by the sum of the aerial impedance and the reactance of the series variometer (ZTOWR - discussed above). This is defined as the "antenna" current. At the radiation resistance in the aerial circuit both the current flowing through it and the power across it are computed.

Thus this subprogram, by assuming a constant voltage on the plates of the power amplifiers recompute the voltage and currents at each frequency, as well as the output power.

The results, in array form, are sent to the MAIN program, and may be printed out in tabular form. Two tables may be printed, omitted, or either selected for output. The first table includes "antenna," helix, Tee, bandwidth resistor current and frequency; the second has transformer, aerial, and radiation resistance currents, as well as radiated power and frequency.

GRAPH:

This subprogram is used to graphically display data which has been previously computed, and possibly presented in tabular form. For

example, it may be of interest to know the variation of the helix and Tee impedance as a function of frequency. Since these values are complex arrays, new arrays consisting of the real and imaginary parts are generated. Then this information may be displayed graphically by use of PTPLOT, using a separate plot for each parameter. The independent variable is the normalized frequency array since deviation from the center frequency is of prime interest.

If desired, two or more arrays may be combined into a single plot, such as the real and reactive portions of a complex impedance, and presented using PLOTIT. This procedure presents both parts of the impedance on the same scale, which aids in determining relative changes as frequency is varied.

ABCD:

This subprogram makes use of the ABCD matrices for the different networks in the antenna system. The desired radiated power used in the AERIAL subprogram to determine the voltage across and the current through the radiation resistance, [defined by the reference VOLTS(5,2) and AMPS(5,2)], is the basic reference.

Subprogram MATRIX is called using the center frequency, and each of the voltages and currents for the various networks is found by appropriate multiplication of matrices. Then subprogram COMP is used to determine the impedance, phase angle, and power at each network, down to the input to the Tee network. This data is then printed in sequence starting at the radiation resistance.

Next the four different transformer combinations are connected to the Tee network. The parameters of voltage, current, impedance, phase angle, and power are determined both at the input to the

transformers and with the primary tuning capacitor connected, for all four combinations.

D. Accessory Programs

These programs are incidental to the main program in that they are used for setting initial conditions, doing special arithmetic manipulations, or displaying certain data. No direct printed output is available from these programs unless specifically noted; the data is used in intermediate steps of various subprograms.

BLOCK DATA

This is a special program used to initialize many secondary variables. In particular, the tuning limits for variable inductors and capacitors are inserted here since they will be "constants" for a given system.

FACT1(A)

This subprogram computes the sum of A squared plus one, which often arises in converting from series to parallel circuits and vice versa.

FACT2(A)

This subprogram computes the quotient of A squared plus one quantity divided by A squared. This is also used in series-parallel transformations.

COMP

This subprogram is called with a complex voltage and current. If either is zero a statement is printed so indicating; otherwise, the complex power and impedance are computed, as is the impedance phase angle, using current as reference.

MULT

This subprogram is called with complex matrices (arrays), up to order 9 by 9. If the orders are acceptable for multiplication (a notice is printed if they are not), the resulting product matrix is sent back to the main program.

PTPLOT

This subprogram is a plotting routine using the computer page printer and paper for output. With two given, equally dimensioned arrays of real numbers, one is plotted against the second, using 90 horizontal spaces on the output paper. The values of the two arrays corresponding to each plotted point are printed. The two extreme values of the dependent variable are printed, and titling for the column listing of the variables (such as "Frequency" for the independent and "Response" for the dependent) is available. If either array passes through zero value an appropriate axis will be printed. The length of the printout (number of independent points plotted) is limited solely by the storage size of the computer.

PLOTIT

This subprogram will plot up to nine dependent arrays of real numbers against one independent array. Basically an extended form of PTPLOT above, this routine uses a horizontal field of 100 points on the page printer, since only the independent variable is specifically listed. A common scale for the dependent variables is used (allowing comparison of various responses) with values marked at the beginning and at 25% locations across the bottom of the plot. Axes, like those in PTPLOT, are available. The independent array may be sorted into

ascending order if desired. Titling is available, such that each curve may be labelled along with its "mark" on the plot. The total number of independent variable points which may be plotted depends on the number of dependent arrays used. All arrays (including the independent) are formed into a single array within the program, which is limited to 1,000 points. Thus three dependent arrays of length 250 may be used, or nine dependent arrays, each of size 100.

E. Variables Used in VLFANT

The choice of variables for VLFANT was made with quick recognition as the main objective. Since names are limited to six alphanumeric characters, in some cases a compromise was necessary. (This is the reason "aerial" is used so much in place of the more common "antenna").

All variables are single precision (16 bits) rather than double precision (32 bits). Although there is some loss in accuracy since numbers of quite different magnitudes are multiplied together (for example inductive values with orders of magnitude of 10^{-6} are multiplied by the radian frequency with order of magnitude of 10^5) the loss is in the least significant digits and is not felt to warrant the use of double precision.

Impedances are all complex, with the exception of pure resistances when they are "given" variables. The complex "s," from Laplace analysis, is used extensively.

Table VII lists the most important variables. Of particular interest are those which must be supplied by the program user, since it is here that changes in the system must be made. A number of

variables not listed will be found in VLFANT, but these are generally used for intermediate steps and are of major concern only when making a detailed study of the programs.

TABLE VII
VARIABLES USED IN VLFANT

Term	Type R - Real C - Complex	Defined By U - User P - Program	Units	Comments
CENFCY	R	U	cycles	Center (operating) frequency
WATTS	R	U	watts	Desired radiated power at center frequency
RAD	R	U	ohms	Aerial radiation resistance
RAS	R	U	ohms	Total aerial resistance (radiation plus loss)
CAP(5,1)	R	U	farads	Aerial static capacitance
COIL(5,1)	R	U	henrys	Aerial inductance
ZOUT	R	U	ohms	Helix input impedance at operating frequency
RBW	R	U	ohms	Bandwidth resistor resistance
PRBW	R	U	watts	Bandwidth resistor dissipation
ZIN	R	U	ohms	Tee input impedance at operating frequency
RBWCH	R	U	henrys	Bandwidth system vario-meter - upper limit
RBWCL	R	U	henrys	Bandwidth system vario-meter - lower limit
CP21H	R	U	farads	Transformer secondary { Cap(1,2) upper limit
CP21L	R	U	farads	
CP23H	R	U	farads	Tee Leg two { Cap(2,3) upper limit
CP23L	R	U	farads	

CL21H	R	U	henrys	Tee Leg one	Coil(2,1) upper limit
CL21L	R	U	henrys		Coil(2,1) lower limit
CL22H	R	U	henrys	Leg two	Coil(2,2) upper limit
CL22L	R	U	henrys		Coil(2,2) lower limit
COIL(2,1)	R	U	henrys	Tee Leg one	Value for coil in Tee section
COIL(1,1)	R	U	henrys	Inductance for primary of each transformer	
CLP(a)	R	U	-	Transformer coupling coefficient (a goes from 1-4)	
TAP(a)	R	U	henrys	Transformer secondary winding (a goes from 1-4)	
RPTP	R	U	ohms	Power amplifier plate-to-plate resistance	
CAP(1,1)	R	U	farads	Transformer primary circuit capacitance	
COIL(3,1)	R	U	henrys	Bandwidth resistor coupling variometer	
K	R	U	-	Number of steps in frequency deviation program	
DEL	R	U	-	Size of each step in frequency deviation	
OMEGA	R	P	radians/sec.	Frequency in radians	
S	C	P	radians/sec.	Complex operator, frequency in radians	
VOLTS(a,b)	C	P	volts	Voltages ("a" gives block, "b" input or output)	
AMPS(a,b)	C	P	amperes	Currents ("a" gives block, "b" input or output)	

ZTOTAL(a,b)	C	P	ohms	Impedance ("a" gives block, "b" input or output)
YTOTAL(a,b)	C	P	mhos	Admittances ("a" gives block, "b" input or output)
POWER(a,b)	C	P	watts	Power ("a" gives block, "b" input or output)
PHASE(a,b)	C	P	degrees (rad.)	Phase angle ("a" gives block, "b" input or output)
COIL(a,b)	R	P	henrys	Inductors ("a" gives block, "b" input or output)
CAP(a,b)	R	P	farads	Capacitors ("a" gives block, "b" input or output)
XL(a,b)	C	P	ohms	Inductive reactance (same indexing as above)
XC(a,b)	C	P	ohms	Capacitive reactance (same indexing as above)
ZONE	C	P	ohms	Tee Leg one impedance
ZTWO	C	P	ohms	Leg two impedance
ZTHREE	C	P	ohms	Leg three impedance
ZANT(L)	C	P	ohms	Aerial input impedance in frequency deviation run
ZHELIX(L)	C	P	ohms	Helix input impedance in frequency deviation run
ZRES(L)	C	P	ohms	Bandwidth circuit impedance in frequency deviation run
ZTEE(L)	C	P	ohms	Tee input impedance in frequency deviation run
ZTOWR(L)	C	P	ohms	Aerial and Coil(4,2) impedance in frequency deviation
QNOW	R	P	-	Q of aerial circuit including loss resistance

SELRES	R	P	cycles	Aerial self-resonant frequency
XFMR1(L)	C	P	ohms	Transformer one unit, primary impedance, frequency run
XFMR2(L)	C	P	ohms	Transformer two units, primary impedance, frequency run
XFMR3(L)	C	P	ohms	Transformer three units, primary impedance, frequency run
XFMR4(L)	C	P	ohms	Transformer four units, primary impedance, frequency run
CURANT(L)	C	P	amperes	Aerial Current during frequency response run
CURTWR(L)	C	P	amperes	Current through ZTOWER(L) frequency run
CURHEL(L)	C	P	amperes	Helix current, frequency run
CURRES(L)	C	P	amperes	Bandwidth resistor current, frequency run
CURTEE(L)	C	P	amperes	Tee network current, frequency run
CURXL(L)	C	P	amperes	Transformer one unit, primary current, frequency run
CURX2(L)	C	P	amperes	Transformer two units, primary current, frequency run
CURX3(L)	C	P	amperes	Transformer three units, primary current, frequency run
CURX4(L)	C	P	amperes	Transformer four units, primary current, frequency run
A(c,d)	C	P	-	Aerial, forward, ABCD matrix
B(c,d)	C	P	-	Helix, forward, ABCD matrix
C(c,d)	C	P	-	Bandwidth resistor, forward, ABCD matrix

D(c,d)	C	P	-	Tee, forward, ABCD matrix
E(c,d)	C	P	-	Transformer one, forward, ABCD matrix
F(c,d)	C	P	-	Transformer one, reverse, ABCD matrix
G(c,d)	C	P	-	Tee reverse, ABCD matrix
O(c,d)	C	P	-	Helix reverse, ABCD matrix
P(c,d)	C	P	-	Aerial reverse, ABCD matrix
R(c,d)	C	P	-	Transformer two, forward, ABCD matrix
T(c,d)	C	P	-	Transformer two, reverse, ABCD matrix
U(c,d)	C	P	-	Transformer three, forward, ABCD matrix
V(c,d)	C	P	-	Transformer three, reverse, ABCD matrix
W(c,d)	C	P	-	Transformer four, forward, ABCD matrix
X(c,d)	C	P	-	Transformer four, reverse, ABCD matrix
EP(c,d)	C	P	-	Amplifier one, forward, ABCD matrix
RP(c,d)	C	P	-	Amplifier two, forward, ABCD matrix
UP(c,d)	C	P	-	Amplifier three, forward, ABCD matrix
WP(c,d)	C	P	-	Amplifier four, forward, ABCD matrix
CURRAD(L)	C	P	amperes	Current through radiation resistance, frequency run
PWROUT(L)	C	P	watts	Power across radiation resistance, freq. run
ZTANK(a)	C	P	ohms	Transformer secondary impedance with power amplifiers connected (a goes 1-4)

V. Discussion

The construction of an antenna system for a high power Very Low Frequency transmitter station is an extensive undertaking. The physical structure is usually very large (but electrically small), and is a compromise from the very beginning. Aerial deficiencies cannot be completely overcome, but by a prudent choice of coupling and matching system full use may be made of the finally accepted system design.

In the past much use has been made of basic theoretical studies followed by modeling studies of the most promising designs. Useful information from these tests has been accurate enough to be used in the final design and also to develop the necessary coupling and matching networks.

A network analysis for the complete system is made first at the limits of the operating frequency range to determine extremes for tunable components. A more detailed analysis is then carried out for the operating frequency. If the transmitted waveform involves frequency deviation (such as with FSK), the antenna system is analyzed at the frequencies corresponding to the maximum deviation encountered. Within this range intermediate values may be obtained by reference to a set of universal curves for the type of circuit involved.

If the antenna system at Northwest Cape is used as an example, the circuit may be analyzed at resonance in terms of input and output parameters at the various network blocks in a relatively short time. A more detailed analysis, such as computation of voltage, current, and power dissipated for each of the individual elements, will take much longer. The complexity increases if the frequency is allowed to vary from resonance, such that a complete analysis becomes very time

consuming. The choice of frequency steps when operating off resonance is important: is five cycles satisfactory or should increments of one-half cycle be used?

Parameter values in the field will vary from those measured in model studies or found from a purely theoretical analysis. If the antenna system is designed with such changes in mind (provisions for shunt capacitance, additional load inductance, variation in loss resistance, etc.), then the final adjustment in the field will be more easily accomplished. To be prepared for such variations a good theoretical analysis is necessary, which requires a rather large amount of time. If a major parameter such as the radiation resistance is found to have a different value in the field, however, the design analysis must be modified in whole, since it is no longer correct.

It is at this point that a computer program for network analysis can be extremely beneficial. A number of such programs have been developed in the last several years by IBM and others. The programs vary in their usefulness, since they are usually very general in design. Within the last year the Jet Propulsion Laboratory has introduced two programs for antenna design, but these are applicable only for specialized antennas at much higher frequencies. While most of these programs could be of some use, more beneficial results could be obtained from a program tailored to the VLF antenna system in particular. The author is aware of only one program other than VLFANT which is so designed, and this program (part of a larger study) apparently has never been publicly disclosed.³³

VLFANT is a general program, tailored to meet the special networks encountered in a VLF antenna system. Once the initial parameters

have been defined (such as top-hat capacitance, radiated power, operating frequency, etc.), settings for tunable components may be determined. The frequency may then be varied at will, using increments of any desired size. Results are printed out and plotted to give added insight into system response if desired. Tuning ranges may be determined for variable components by choosing operating frequencies at the ends of the VLF band. Impedances, voltages, currents, phase angles, and so forth may be easily found. Any parameter may be modified and a new set of results will be available with only a few minutes of computer time.

One area not covered in VLFANT is the operation of the Class C power amplifiers normally encountered in high power transmitter. In the analysis the power amplifiers are considered to be constant voltage generators. This is a reasonable assumption at the resonant frequency where the antenna system load is designed to be a pure resistance, but off resonance the load will vary and include a reactance term, and the constant voltage assumption will no longer be valid. A thorough analysis is difficult, since the effective plate resistance (treated as the generator internal resistance) is a function of various parameters including the load impedance magnitude and phase angle.

One empirical study of this problem has been made, where an actual circuit was constructed and various measurements made and plotted. While this gives a good indication of Class C operation in general, it is good only for the tube and circuit tested, and does not yield a theoretical generalization of the problem.³⁴

One student at the Naval Postgraduate School has written a computer program involving the use of Class C amplifiers as part of his thesis work on network synthesis using active devices.³⁵ Basic tube parameters (plate resistance, output capacitance, amplification factor, etc.) and maximum ratings (plate dissipation, grid drive, plate voltage, bias levels, etc.) are first entered for the tube under study. Then the minimum output power, tube efficiency and bandwidth desired at the operating frequency are entered. The program computes the necessary operating parameters to meet the required conditions, and indicates which requirement is critical if the desired conditions cannot be met. An LC tank circuit is the tube load and a value for the necessary inductance is given for desired operation.

While this program is not immediately usable with VLFANT, it appears to be an excellent starting point for the inclusion of Class C amplifier operation. A combination of the Class C amplifier-VLFANT programs should give all information necessary for a complete VLF transmitter-antenna system analysis.

A second area of interest is the transient response of the antenna system when fed with an FSK input. The ABCD matrices developed in VLFANT may be used to form a transfer function in a Laplace analysis of the circuit response, but due to limitations in time such a study was not undertaken in this thesis. It should be noted that in the circuit analysis reported in DECO Interim Report No. 34-C-6 an FSK signal using a modulation index of one produced less transient response degradation than did a similar signal with an index of one-half. In no case, however, did the transient distortion go to zero, so strict

attention should be paid to this subject since in systems operating near breakdown levels transients may cause severe damage to the system.

With respect to the Northwest Cape VLF station used as the model in VLFANT, the output data was found to be in excellent agreement with that measured by the facility itself. The numerical examples used in the Basic Principles section of this thesis was taken from original design information supplied while the program was being written. After the transmitter installation was completed, thorough site measurements were made and some of the parameters were found to be noticeably different from what had been predicted. In particular, the loss resistance was lower than first thought, and a 40 foot length of bus bar added some series inductance to the aerial. These variations were easily taken care of in VLFANT: the new data was entered into the program and with only a few minutes of computer time the new output data was available.

VI. CONCLUSIONS

The design and construction of VLF transmitting antenna systems is an involved and expensive project. With the increased importance of VLF communications in the past few years efficient and reliable operation of all components of such a system becomes even more important.

The best analysis possible of a proposed system must be achieved, and all data relevant to existing system should be up-to-date, so that maximum overall efficiency is attained.

Computer programs designed for use on high-speed digital computers help to achieve an accurate analysis of systems in a short time. VLFANT, designed expressly for VLF antenna systems, will provide information of relevance to this specialized field, and may be used from the beginning design stages through to a fully operational status. When tested with the Northwest Cape transmitter installation as a model, output data was in excellent agreement with data measurements made in the field. A large quantity of additional information, either too difficult or time consuming to actually measure, was also provided, which gives a deeper insight into the operation of the station.

The digital computer program developed here has only scratched the surface of the many advantages available in using such a tool for the optimum design of VLF antenna systems. Some areas requiring additional study have been pointed out (Class C amplifier operation, transient response, etc.), and by an extended use of a program such as VLFANT, other such areas may be determined.

Full application of such a program should be made, especially in the all important design stage, for as has been pointed out before there are two ways to design an antenna system: "(1) design the unit

properly, in a comfortable office during the day, or (2) slowly freeze, night after night, while trying to make a poor design work."¹⁵

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APPENDIX A

BANDWIDTH RESISTOR NETWORK:

The "Q" of an aerial is determined by the largest reactance together with the total resistance present in the circuit, and for most VLF aerals may be expressed by:

$$Q_{\text{aerial}} = \frac{|X_c|}{R} \quad \dots(1)$$

where Q_{aerial} = Quality factor for aerial

X_c = Value of aerial static capacitance

R = Resistance

When speaking of the aerial alone, R is the radiation resistance; for the antenna system as a whole R is the sum of the radiation and loss resistances. See Figure 44. The corresponding bandwidth is given by:

$$BW = \frac{f_o}{Q} \quad \dots(2)$$

where BW = 3 db bandwidth in Hz

f_o = operating frequency in Hz

Similar definitions for Q and bandwidth are applicable for series circuits at their resonant frequency.

Networks in the complete antenna system are designed to be lossless, that is, they have extremely low loss resistances and have reactances much greater than the resistance present. When these networks are used for impedance matching at the operating frequency their reactance terms cancel out such that no new reactance is added to the overall system, and being lossless no additional resistance is added.

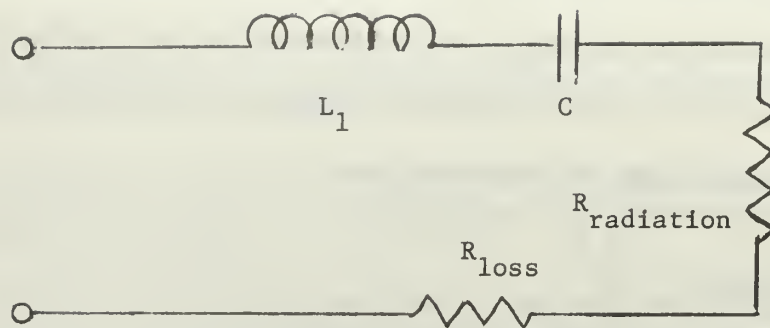


Figure 44. Basic Aerial Circuit

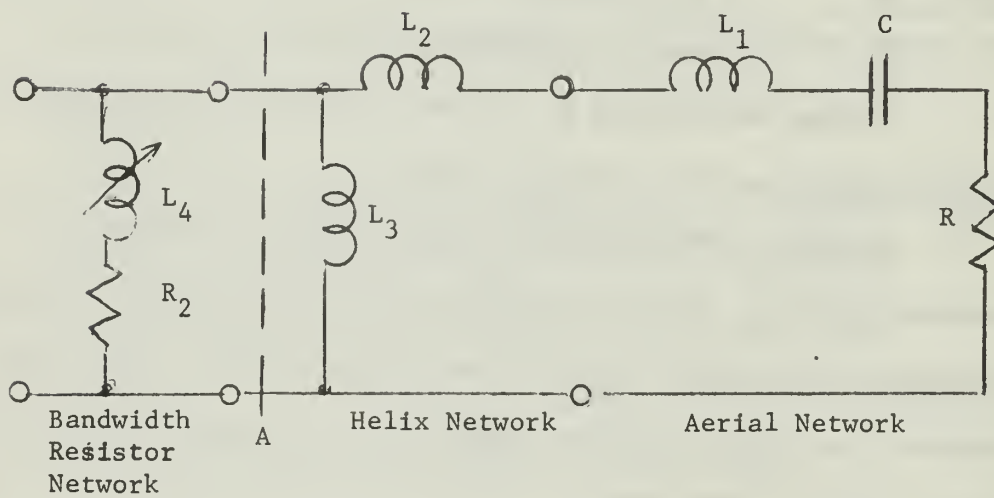


Figure 45. Basic Bandwidth Widening Circuit

Figure 45 shows a helix impedance matching circuit connected to the basic aerial circuit. To the right of cut A the input impedance will appear as a pure resistance at the resonant frequency. There might be a tendency to apply Equations (1) and (2) at this input, but they no longer apply since the circuit is no longer a simple series circuit. To the left of cut A a new Bandwidth Resistor network has been connected. By varying inductance L_4 the effect of resistance R_2 is changed.

To properly evaluate the actual circuit Q when the Bandwidth Resistor is added to the network, a definite procedure must be used. In Figure 46 all series reactances in the helix-aerial circuit have been combined; from the design of the helix network the resulting reactance will be capacitive. The series Bandwidth Resistor circuit has been put into its equivalent parallel form.

Figure 47 shows the aerial RC' series network replaced by its equivalent parallel form - $R_p C_p'$, and the parallel resistance of the bandwidth resistor has been moved to the far right hand end of the network. The resistances $R_p - R_2'$ may now be combined, and then the resistance sum and C_p' combination put into series form, $R_{new} - C'$. See Figure 48.

The capacitive reactance undergoes little change during the above transformation, so C' may be put back into a form similar to the original circuit, as shown in Figure 49. Now a new Q for the circuit may be defined.

$$Q_{new} = \frac{X_c}{R_{new}} \quad \dots(3)$$

The procedure described above is useful where an assumed value for the Bandwidth Resistor network coupling inductor is used.

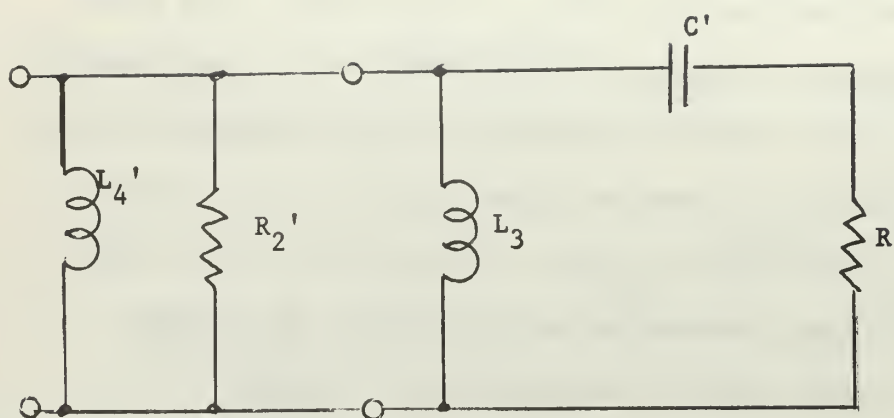


Figure 46. Reactances Summed

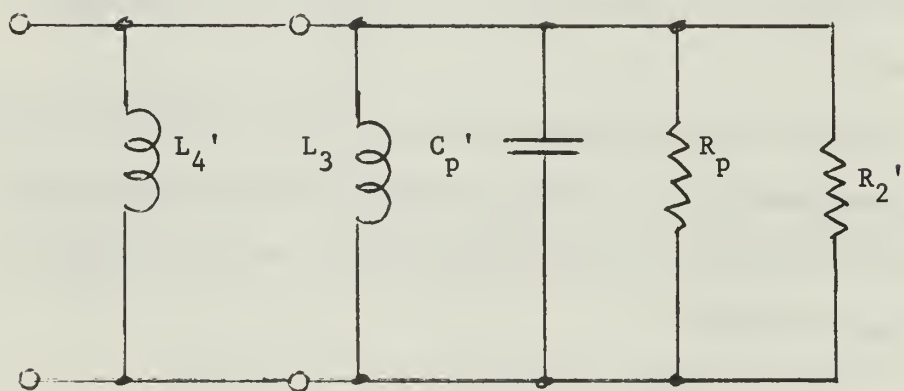


Figure 47. Parallel Representation

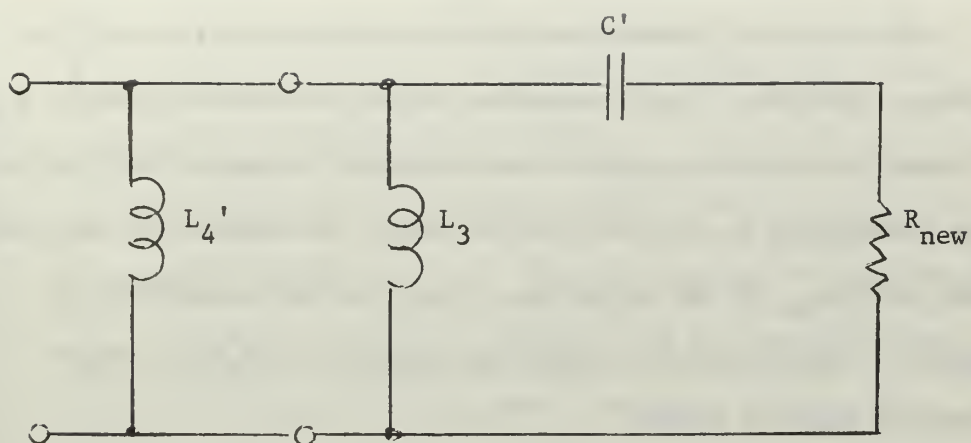


Figure 48. Series Form of Aerial Circuit

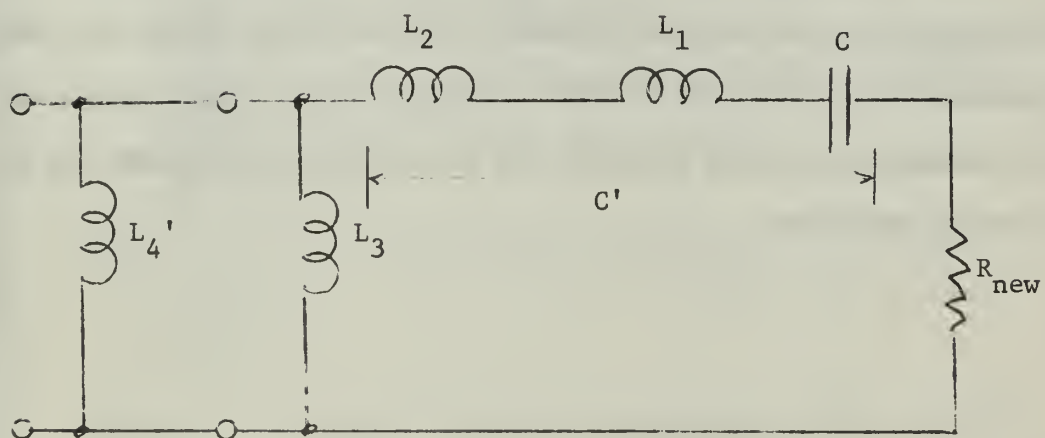


Figure 49. Resultant Widened Circuit

As L_4 is varied the resulting parallel resistance R_2' will vary, resulting in a range of values for Q_{new} .

This type of transformation above will hold for only one frequency since the reactance values effect the final value of R_{new} . Additionally, the helix circuit was designed to match the original aerial resistance R , and the desired input impedance will no longer be seen with R_{new} in the circuit. If the circuit impedance is computed at other than the operating frequency, an even larger discrepancy will be noted.

The question then is how to properly evaluate the effect of the Bandwidth Resistor network. This can be done by observing the current flowing into the series aerial circuit and through the radiation resistance. An ammeter is placed in series with the connection between the helix and aerial circuit, at the junction of L_1 and L_2 . Then when voltage is applied at the input to the overall circuit, Figure 45, current will divide into three paths: through L_2 , L_3 and L_4 .

In actual operation the voltage at the circuit input will be different with the Bandwidth Resistor in the system since the overall impedance will draw more current through previous stages (such as a Tee impedance matching network) and the new system response may be properly evaluated.

MAJOR SURPROGRAMS

```
//VLFANT JOB (EAX5,09FT,5.5,300),'GOBBEL',MSGLEVEL=1
// EXEC FORTCLG
//FCRT.SYSIN DD *
```

THIS PROGRAM IS WRITTEN FOR THE ANTENNA COUPLING NETWORK
IN USE AT THE NAVY VLF STATION AT NORTHWEST CAPE. USING
MEASURED VALUES FOR THE ANTENNA ITSELF, THEORETICAL VALUES
FOR THE VARIABLE TUNING ELEMENTS, THEIR SETTINGS WILL BE
DETERMINED FOR THE RESONANT FREQUENCY. LIMITS FOR TUNING
RANGES, VOLTAGE BREAKDOWN, MAXIMUM CURRENTS, ETC., WILL BE
CHECKED, AND ANY DISCREPANCIES NOTED. THE FREQUENCY WILL THEN
BE VARIED ON EITHER SIDE OF RESONANCE, AND THE INPUT IMPEDANCE
TO THE AFRIAL, COUPLING VARIOMETER, AND TEE SECTION WILL BE
COMPUTED. IMPEDANCES FOR USE OF ONE TO FOUR TRANSFORMERS,
WILL ALSO BE DETERMINED. ADDITIONALLY, VOLTAGES AND CURRENTS
OVER THE OPERATING FREQUENCY RANGE WILL BE DETERMINED.

```
DIMENSION ALPHA (241), BETA (241), GAMMA (241), EATA (241)
DIMENSION EPSI(241), PSI(241)
DIMENSION Y1(1), Y2(1), Y3(1), Y4(1), Y5(1), Y6(1), Y7(1),
Y8(1), Y9(1)
DIMENSION TITLE1(1), TITLE2(1), TITLE3(1), TITLE4(1), TITLE5(1)
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```
COMPLEX S, XC(5,3), XL(5,3), XTOTAL(5,2), YTOTAL(5,2),
ZTOTAL(5,2), ZT, AMPS(5,3), VOLTS(5,3), POWER(5,2),
ZZONE, ZTWO, ZTHREE
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COMPLEX PRIMRY, TOP, BOTTOM, XFMR1(241), XFMR2(241),
XFMR3(241), XFMR4(241), ZANTI(241), ZTOWR(241), ZHELIX(241),
ZZRES(241), ZTEE(241)
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COMPLEX CURANT(241), CURTWR(241), CURHEL(241), CURRES(241),
ICURTEE(241), CURX1(241), CURX2(241), CURX3(241), CURX4(241)
COMPLEX CURRAD(241), PWRROUT(241)
COMPLEX ZTANK(4), ZLOAD
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```
COMPLEX A(2,2), B(2,2), C(2,2), D(2,2), E(2,2), F(2,2), G(2,2),
H(2,2), P(2,2), R(2,2), T(2,2), U(2,2), V(2,2), W(2,2), X(2,2),
ZUU(2,2), VV(2,2), EP(2,2), RP(2,2), UP(2,2), WP(2,2), WW(2,2)
COMPLEX XX(2,2)
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```
COMMON/A/ COIL(5,3), CAP(5,3), RAS, RDC, RAD, RBW, PI
COMMON/B/ CPL(4), PHASE(5,2), TAP(4), COILM(4)
COMMON/C/ ZONE, ZTWO, ZTHREE
COMMON/D/ TOWER, SELRES, WATTS, QNOW, PRBW, PRBWKW, PWRKW
COMMON/E/ VOLTS, AMPS, XC, XL, XTOTAL, YTOTAL, ZTOTAL
COMMON/F/ CP21H, CP21L, CP23H, CP23L, CL21H, CL21L, CL22H, CL22L
COMMON/G/ GENFCY, OMEGA, S
COMMON/H/ EA, EC, ED, EE, EF, EG, EQ, RBWCL, RBWCH
COMMON/I/ CAH, CAL, CBH, CBL, CCH, CCL, CDH, CDL
COMMON/J/ FREQ(241), DIV(241), ZANT, ZHELIX, ZRES, ZTEE, ZTOWR
COMMON/K/ XFMR1, XFMR2, XFMR3, XFMR4
COMMON/L/ CURANT, CURTWR, CURHEL, CURRES, CURTEE
COMMON/M/ CURX1, CURX2, CURX3, CURX4
COMMON/N/ A, B, C, D, E, F, G, H, P, R, T, U, V, W, X, UU, VV
COMMON/O/ QVREQ(41), QVQA(41), QVOL(41), QVBWA(41), QVBWL(41)
COMMON/P/ DUM, ZLOAD, RPTP, QPRI(4), CAP1(4)
COMMON/Q/ EP, RP, UP, WP
COMMON/R/ CURRAD, PWRROUT
COMMON/S/ ALPHA, BETA, GAMMA, EATA, EPSI, PSI
COMMON/Z/ IBAR(120)
```

```
GENFCY = 15.525E3
RAD = 0.142
RAS = 0.186
```

THE FOLLOWING ARE CONSTANTS FOR THE ENTIRE SYSTEM

```
ZIN = 20.0
ZOUT = 12.5
CHECK = 0.0
MODE = 0
K = 69
DEL = 20.0
```

THE FOLLOWING PUTS DATA IN OPERABLE FORM AND ADDS NECESSARY OPERATING
VARIABLES TO BE USED IN THE REST OF THE PROGRAM

```
COIL(3,1) = RBWCH
```

```

101 OMEGA = 2. * PI * CENFCY
102 S = CMPLX ( 0.0, OMEGA )
103 FQ = CENFCY * 1.0E-3
104
105 C
106 RDC = RAS - RAD
107 WLEN = 3.0ER / CENFCY
108
109 C
110 C
111 CALL PRINT
112 CALL AERIAL
113 CALL HELIX ( ZOUT, 1 )
114 CALL RESIST ( 0.0, VQ, 1 )
115
116 C
117 WRITE (6,100)
118 CALL QVARY ( 0 )
119 CALL PLOTIT ( 41, 0, QVFREQ, QVQA, QVWA, QVOL, QVBWL,
120 1Y5, Y6, Y7, Y8, Y9, 41, 41, 41, 1, 1, 1, 1, 1,
121 2'AERIAL "Q" VS. FREQUENCY FREQ-KC
122 4'AERIAL BANDWIDTH (CYCLES) AERIAL "Q" WITH LOSS RESIST.
123 5'AERIAL BANDWIDTH(WITH LOSS)
124 6TITLE4, TITLE5 )
125
126 C
127 CALL TEE ( ZIN, ZOUT )
128 CALL TANK
129 CALL MATRIX ( CENFCY, 1 )
130 CALL ABCD
131 CALL DELTA ( CENFCY, K, 1.0, 0, 4 )
132 CALL GRAPH ( K, 3, 1 )
133 CALL ANTAMP ( K, 4, 4, 0 )
134 CALL GRAPH ( K, 3, 2 )
135
136 C
137 100 FORMAT ( '1', 20X, 'VARIATION IN "Q" AND BANDWIDTH FOR AERIAL',
138 1' WITH AND WITHOUT LOSS RESISTANCE', / )
139 101 FORMAT ( '0', 5X, F10.2, 5( 2G10.3) )
140 300 FORMAT ( '1', 30X, 'VARIATION IN "Q" VERSUS COIL SETTING', / )
141 806 FORMAT( '0', 2X, 'XFMR5', 8X, 5HVOLTS, 22X,
142 14HAMPS, 19X, 9HIMPEDANCE, 10X, 5HPHASE, 11X, 5HPOWER)
143 END

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SUBROUTINE PRINT

THIS SUBROUTINE WILL PRESENT THE MAJOR
PARAMETERS FOR THE ANTENNA SYSTEM.

COMMON/A/ COIL(5,3), CAP(5,3), RAS, RDC, RAD, RBW, PI
COMMON/B/ CPL(4), PHASE(5,2), TAP(4), COILM(4)
COMMON/D/ TOWER, SELRES, WATTS, QNOW, PRBW, PRBKW, PWRKW
COMMON/F/ CP21H, CP21L, CP23H, CP23L, CL21H, CL21L, CL22H, CL22L
COMMON/H/ FA, FC, FD, EE, EF, EG, FQ, RBWCL, RBWCH
COMMON/I/ CAH, CAL, CBH, CBL, CCH, CCL, CDH, CDL
COMMON/P/ DUM, ZLOAD, RPTP, QPRI(4), CAP1(4)
COMMON/Z/ IBAR(120)

COMPLEX ZLOAD

AAA = CAP(5,1) * 1.0E6
AAB = COIL(5,1) * 1.0E6
CAH = CP21H * 1.0E6
CAL = CP21L * 1.0E6
CBH = CP23H * 1.0E6
CBL = CP23L * 1.0E6
CCH = CL21H * 1.0E6
CCL = CL21L * 1.0E6
CDH = CL22H * 1.0E6
CDL = CL22L * 1.0E6
CEH = RBWCH * 1.0E6
CEL = RBWCL * 1.0E6
EA = COIL(1,1) * 1.0E6
EC = TAP(1) * 1.0E6
ED = TAP(2) * 1.0E6
EE = TAP(3) * 1.0E6
EF = TAP(4) * 1.0E6
EG = CAP(1,1) * 1.0E6
PWRKW = WATTS * 1.0E-3
PRBKW = PRBW * 1.0E-3

THE FOLLOWING PRESENTS THE INITIAL DATA AND COMPONENT RANGES

WRITE (6,1000)
WRITE (6,1002) (IBAR(I), I = 1,113)
WRITE (6,1005) (IBAR(I), I = 1,45)
WRITE (6,1010) FQ, PWRKW
WRITE (6,1020) RAD, RDC, AAA, AAB
WRITE (6,1040) RBW, PRBKW
WRITE (6,1045) CEL, CEH
WRITE (6,1050)
WRITE (6,1054) CBL, CBH
WRITE (6,1057) CCL, CCH, CDL, CDH
WRITE (6,1060) EA
WRITE (6,1075) EG
WRITE (6,1076) CAL, CAH
WRITE (6,1062)
WRITE (6,1064) EC, ED, EE, EF
WRITE (6,1066) CPL(1), CPL(2), CPL(3), CPL(4)
WRITE (6,1080) RPTP
WRITE (6,2000)
WRITE (6,2001) (IBAR(I), I=1,59)

1000 FORMAT (1H1, 15X, 'OUTPUT DATA FOR THE VLF ANTENNA AT ',
11NORTHWEST CAPE, 1X)
1002 FORMAT (1H1, 1X, 113A1, '////')
1005 FORMAT (1H1, 1X, 'THESE ARE THE BASIC ANTENNA SYSTEM PARAMETERS')
1007 FORMAT (1H1, 1X, 45A1)
1010 FORMAT(1H0, 10X, 16HMAJOR PARAMETERS, '//, 30X,
116HCENTER FREQUENCY, F14.3, ' KHZ', '//, 30X,
214HPOWER RADIATED, 6X, F10.3, 4H KW)
1020 FORMAT (1H0, 10X, 'AERIAL CIRCUIT', '//, 30X,
12CHRADIATION RESISTANCE, F10.3, 6H OHMS, '//, 30X,
215HLOSS RESISTANCE, F15.3, 6H OHMS, '//, 30X,
319HTOP-HAT CAPACITANCE, F11.3, 8H UFARAD, '//, 30X,
420HDOWN-LEAD INDUCTANCE, F10.3, 8H UHENRY)
1040 FORMAT(1H0, 10X, 26HBANDWIDTH RESISTOR CIRCUIT, '//, 30X,
11CHRESISTANCE, 10X, F10.3, 6H OHMS, '//, 30X,
22CHMAXIMUM DISSIPATION, F10.3, 4H KW)
1045 FORMAT(1H0, 29X, 15HCOIL TUNES FROM, 5X, F10.3,
15H TO, F10.3, 8H UHENRY)
1050 FORMAT(1H0, 10X, 11HTEE NETWORK, '//, 53X,
17HMINIMUM, 8X, 7HMAXIMUM)
1054 FORMAT(1H0, 29X, 7HCAP ONE, 13X, F10.3, 5X, F10.3, 8H UFARAD)
1057 FORMAT(1H0, 29X, 8HCOIL ONE, 12X, F10.3, 5X, F10.3, 8H UHENRY,
11H, 30X, 8HCOIL TWO, 12X, F10.3, 5X, F10.3, 8H UHENRY)
1060 FORMAT (1H0, 10X, 12HTANK CIRCUIT, '//, 30X,
13HEACH PRIMARY HAS INDUCTANCE OF, F10.3, 8H UHENRY)
1062 FORMAT (1H0, 30X, 17HNO. OF POWER AMPS, 19X, 3HONE, 6X,
13HTWO, 5X, 5HTHREE, 5X, 4HFOUR)
1064 FORMAT(1H0, 30X, 23HEACH SECONDARY (UHENRY), 8X, 4F9.2)
1066 FORMAT(1H0, 30X, 20HCOUPLING COEFFICIENT, 12X, 4F9.3)
1075 FORMAT (1H0, 29X, 'PRIMARY TUNING CAPACITOR', 6X, F10.3, ' UFARAD')
1076 FORMAT (1H0, 29X, 'SECONDARY CAPACITOR TUNES', 5X, F10.3,
1H TO, F10.3, ' UFARAD')
1080 FORMAT (1H0, 1, 30X, 'PLATE-TO-PLATE RESISTANCE', 5X,
1F10.3, ' OHMS')
2000 FORMAT (1H1, 'THE FOLLOWING DATA IS COMPUTED FOR THE ANTENNA ',
1HAT RESONANCE')
2001 FORMAT (1H1, 59A1, '////')


```

1  C  SUBROUTINE HELIX ( ZOUT, MODE )
2
3  C
4  C      THIS SUBROUTINE WILL DETERMINE THE VALUES OF
5  C      THE HELIX REQUIRED, AND SETTINGS FOR THE
6  C      SERIES AND COUPLING VARIOMETERS.
7
8  C      IF MODE = 0  USE ORIGINAL METHOD
9  C      MODE = 1  USE ZERO ANGLE METHOD
10
11 C
12 C      CCMPLX S, XC(5,3), XL(5,3), XTOTAL(5,2), YTOTAL(5,2),
13 C      1ZTOTAL(5,2), ZT, AMPS(5,3), VOLTS(5,3), POWER(5,2),
14 C      ZZONE, ZTWO, ZTHREE
15
16 C      CCMON/A/ COIL(5,3), CAP(5,3), RAS, RDC, RAD, RBW, PI
17 C      CCMON/E/ VOLTS, AMPS, XC, XL, XTOTAL, YTOTAL, ZTOTAL
18 C      CCMON/G/ CENFCY, OMEGA, S
19 C      CCMON/Z/ IBAR(120)
20
21 C      IF ( MODE ) 1,1,2
22
23 C      1 XL(4,3) = - XTOTAL(5,1)
24 C      COIL(4,3) = (CABS(XL(4,3)))/OMEGA
25 C      XL(4,1) = CMPLX ( 0.0, SQRT(ZOUT * RAS) )
26 C      COIL(4,1) = (CABS(XL(4,1)))/OMEGA
27 C      COIL(4,2) = COIL(4,3) - COIL(4,1)
28 C      XL(4,2) = S * COIL(4,2)
29 C      XTOTAL(4,2) = XTOTAL(5,1) + XL(4,2)
30 C      GO TO 3
31
32 C      2 XTOTAL(4,3) = CMPLX(0.0, SQRT(RAS * (ZOUT-RAS) ) )
33 C      XL(4,2) = CMPLX(0.0, CABS(XTOTAL(4,3) * XTOTAL(5,1) ) )
34 C      XTOTAL(4,2) = XTOTAL(5,1) + XL(4,2)
35 C      TOPNEW = ( (RAS**2) + (AIMAG( XTOTAL(4,2) ) **2) )
36 C      XL(4,1) = CMPLX ( 0.0, TOPNEW / AIMAG( XTOTAL(4,3) ) )
37 C      COIL(4,1) = AIMAG( XL(4,1) ) / OMEGA
38 C      COIL(4,2) = AIMAG( XL(4,2) ) / OMEGA
39
40 C      3 CONTINUE
41 C      BA = ( OMEGA * CABS( XTOTAL(4,2) ) )
42 C      BB = ( OMEGA * COIL(4,1) ) - CABS( XTOTAL(4,2) )
43 C      TOP = RAS * ( ( OMEGA * COIL(4,1) ) ** 2 )
44 C      TIP = (RAS **2) * (OMEGA * COIL(4,1) )
45 C      BOTTOM = ( RAS ** 2 ) + (BB ** 2 )
46 C      TOPTWO = COIL(4,1) * BA * BB
47 C      ZTOTAL(4,1) = CMPLX(TOP/BOTTOM, (TIP-TOPTWO)/BOTTOM )
48 C      VOLTS(4,1) = VOLTS(5,1) + (AMPS(5,1) * XL(4,2) )
49 C      AMPS(4,1) = AMPS(5,1) + VOLTS(4,1)/XL(4,1)
50 C      AA = COIL(4,2) * 1.0E6
51 C      AB = COIL(4,1) * 1.0E6
52
53 C      WRITE (6,400)
54 C      WRITE (6,401) (IBAR(I), I=1,20 )
55 C      WRITE (6,405) ZOUT
56 C      WRITE (6,410) AA, AB
57 C      WRITE (6,420) ZTOTAL(4,1)
58
59 C      400 FORMAT ( '0', 'DATA FOR HELIX HOUSE' )
60 C      401 FORMAT ( '+', 20A1 )
61 C      405 FORMAT ( '0', 19X, 'DESIRED OUTPUT IMPEDANCE', F15.3, ' OHMS' )
62 C      410 FORMAT(1H0, 19X, 11HSERIES COIL, 18X, F10.3, 8H UHENRY, //,
63 C      120X, 13HCOUPLING COIL, 16X, F10.3, 8H UHENRY)
64 C      420 FORMAT(1H0, 19X, 28HAT RESONANCE, INPUT IMPEDANCE, 5X,
65 C      12G10.5, 6H OHMS)
66
67 C      AMPS(3,1) = AMPS(4,1)
68 C      VOLTS(3,1) = VOLTS(4,1)
69
70 C      RETURN
71 C      END
72
73
74
75
76
77 C  SUBROUTINE TANK
78
79 C
80 C      THIS SUBROUTINE WILL DETERMINE THE INPUT
81 C      IMPEDANCE THAT THE CLASS-C AMPLIFIER TUBES
82 C      WILL SEE WHEN THE ANTENNA SYSTEM IS CONNECTED,
83 C      FOR USE OF 1, 2, 3, AND 4 POWER AMPLIFIERS.
84
85 C
86 C
87 C      CCMPLX S, XC(5,3), XL(5,3), XTOTAL(5,2), YTOTAL(5,2),
88 C      1ZTOTAL(5,2), ZT, AMPS(5,3), VOLTS(5,3), POWER(5,2),
89 C      ZZONE, ZTWO, ZTHREE
90
91 C      CCMPLX BOTTCM, G, ZLOAD, X
92
93 C      COMMON/A/ CCIL(5,3), CAP(5,3), RAS, RDC, RAD, RBW, PI
94 C      COMMON/B/ CPL(4), PHASE(5,2), TAP(4), COILM(4)
95 C      COMMON/E/ VOLTS, AMPS, XC, XL, XTOTAL, YTOTAL, ZTOTAL
96 C      COMMON/F/ CP21H, CP21L, CP23H, CP23L, CL21H, CL21L, CL22H, CL22L
97 C      COMMON/G/ CENFCY, OMEGA, S
98 C      COMMON/H/ EA, EC, ED, EE, EF, EG, EQ, RBWCL, RBWCH
99 C      COMMON/I/ CAH, CAL, CBH, CBL, CCH, CCL, CDH, CDL
100 C      COMMON/P/ DUM, ZLCAD, RPTP, QPRI(4), CAP1(4)
101 C      COMMON/Z/ IBAR(120)

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101 C      XL(1,1) = S * COIL(1,1)
102 CAP(1,1) = 1.0 / (OMEGA * AIMAG( XL(1,1) ) )
103 XC(1,1) = 1.0 / (S * CAP(1,1) )
104 FF = CAP(1,1) * 1.0E6
105 WRITE(6,103)
106 WRITE(6,101) (IBAR(I), I=1,21)
107 WRITE(6,105) EA
108 WRITE(6,106) FF
109 WRITE(6,110) RPTP
110 WRITE(6,115) ZTOTAL(2,1)
111
112 C
113 DC 2 LIMA = 1.4
114 XL(1,2) = CMPLX( 0.0, OMEGA * TAP(LIMA) )
115 COILM(LIMA) = CPL(LIMA) * SQRT( COIL(1,1) * TAP(LTMA) )
116 TOP = (OMEGA * COILM(LIMA) ) **2
117 XC(1,2) = -( LIMA*XL(1,2) ) + AIMAG(ZTOTAL(2,1) )
118 CAP1(LIMA) = 1.0 / (OMEGA * CABS( XC(1,2) ) )
119 ZLOAD = ( XC(1,2) + ZTOTAL(2,1) ) / LIMA
120 BOTTOM = XL(1,2) + ZLOAD
121 G = XL(1,1) + ( TOP / BOTTOM )
122 QPRI(LIMA) = ABS( AIMAG(G) ) / REAL(G)
123 R = FACT1( QPRI(LIMA) ) * REAL(G)
124 X = CMPLX( 0.0, FACT2( QPRI(LIMA) ) * AIMAG(G) )
125 VTOTAL(1,1) = (1.0/XC(1,1)) + (1.0/X) + (1.0/R)
126 ZTOTAL(1,1) = 1.0 / VTOTAL(1,1)
127
128 C
129 CA = CAP1(LIMA) * 1.0E6
130 EB = TAP(LIMA) * 1.0E6
131 EH = COILM(LIMA) * 1.0E6
132 WRITE(6,125) LIMA
133 WRITE(6,145) EB, EH, CPL(LIMA)
134 WRITE(6,150) CA
135
136 C
137 IF ( CP21H -CAP1(LIMA)) 20, 21, 21
138 20 WRITE(6,240) CAH
139 GC TO 22
140 21 IF ( CP21L -CAP1(LIMA)) 22, 22, 23
141 23 WRITE(6,245) CAL
142 22 CONTINUE
143 WRITE(6,155) ZLOAD
144 WRITE(6,160) ZTOTAL(1,1)
145 2 CONTINUE
146
147 C
148 100 FORMAT ( '0', 'DATA FOR TANK CIRCUIT' )
149 101 FORMAT ( '+', 21A1 )
150 105 FORMAT ( '0', 10X, 'FOR EACH POWER AMPLIFIER-',
151 126H THE PRIMARY INDUCTANCE IS, F19.3, 8H UHENRY )
152 106 FORMAT ( '0', 36X, 'PRIMARY CAPACITOR SET AT', F20.3, ' UFARAD' )
153 110 FORMAT ( '0', 36X, 'THE DESIRED PLATE-TO-PLATE LOAD IS',
154 1F10.3, ' OHMS', // )
155 115 FORMAT ( '0', 36X, 'THE NETWORK LOAD IS', 2G15.5, ' OHMS' )
156 125 FORMAT ( 1H0, 10X, 'FOR', 12, 2X, ' POWER AMPLIFIERS' )
157 145 FORMAT(1H0, 20X, 28HEACH SECONDARY INDUCTANCE IS,
158 12X, F10.3, 8H UHENRY, //, 21X, 20HMUTUAL INDUCTANCE IS, 10X,
159 2F10.3, 8H UHENRY, //, 21X, 23HCOUPLING COEFFICIENT IS, 7X, F10.3)
160 150 FORMAT ( '0', 20X, 'SECONDARY CAPACITOR SET AT', F14.3, ' UFARAD' )
161 155 FORMAT ( '0', 20X, 'LOAD SEEN BY SECONDARY', 2G15.5, ' OHMS' )
162 160 FORMAT ( '0', 7, 21X, 'PLATE-TO-PLATE LOAD IS' 2G15.5, ' OHMS', // )
163 240 FORMAT ( 1HC, 20X, 'CAP(1,2)', 2X, 'TOO HIGH MAX VALUE IS',
164 1F7.3, ' UFD' )
165 245 FORMAT ( 1HC, 20X, 'CAP(1,2)', 2X, 'TOO LOW. MIN VALUE IS',
166 1F7.3, ' UFD' )
167
168 C
169 RETURN
170 END

```

SUBROUTINE TEE (ZIN, ZOUT)

THIS SUBROUTINE WILL DETERMINE THE SETTINGS
FOR THE TEE MATCHING NETWORK TO MATCH THE
HELIX COIL IMPEDANCE TO THE OUTPUT TRANSFORMERS.

CCOMPLEX S, XC(5,3), XL(5,3), XTOTAL(5,2), YTOTAL(5,2),
ZTOTAL(5,2), ZT, AMPS(5,3), VOLTS(5,3), POWER(5,2),
ZZONE, ZTWO, ZTHREE

CCOMMON/A/ COIL(5,3), CAP(5,3), RAS, RDC, RAD, RBW, PI
COMMON/C/ ZONE, ZTWO, ZTHREE
COMMON/E/ VOLTS, AMPS, XC, XL, XTOTAL, YTOTAL, ZTOTAL
COMMON/F/ CP21H, CP21L, CP23H, CP23L, CL21H, CL21L, CL22H, CL22L
COMMON/G/ GENFCY, OMEGA, S
COMMON/I/ CAH, CAL, CBH, CBL, CCH, CCL, CDH, COL
COMMON/Z/ IBAR(120)

ZTEE= SQRT (ZIN * ZOUT)
CAP(2,3) = 1.0 / (OMEGA * ZTEE)
CCIL(2,2) = ZTEE / OMEGA
XL(2,2) = CMPLX(0.0, OMEGA * COIL(2,2))
XC(2,3) = 1.0 / (S * CAP(2,3))
XL(2,1) = CMPLX(0.0, ZTEE)
COIL(2,1) = AIMAG (XL(2,1)) / OMEGA

ZCNE = (S * CCIL(2,1))
ZTWO = (S * CCIL(2,2))
ZTHREE = (1.0 / (S * CAP(2,3)))

CB = CAP(2,3) * 1.0E6
CC = COIL(2,1) * 1.0E6
CD = COIL(2,2) * 1.0E6
Z1 = AIMAG (ZONE)
Z2 = AIMAG (ZTWO)
Z3 = AIMAG (ZTHREE)

WRITE (6,200)
WRITE (6,201) (IBAR(I), I=1,20)
WRITE (6,202) ZIN, ZOUT
WRITE (6,210) ZTEE, Z1, CC
WRITE (6,220) Z2, CD
WRITE (6,230) Z3, CB

22 LCOIL = 1
IF (CL21H - COIL(2,1)) 24, 25, 25
24 WRITE (6, 250) LCCIL, CCH
GC TO 26
25 IF (CL21L - COIL(2,1)) 26, 26, 27
27 WRITE (6, 255) LCOIL, CCL
26 LCOIL = 2
IF (CL22H - COIL(2,2)) 28, 29, 29
28 WRITE (6, 250) LCOIL, CDH
GC TO 30
29 IF (CL22L - COIL(2,2)) 30, 30, 31
31 WRITE (6, 255) LCCIL, COL
30 LCAP = 1
IF (CP23H - CAP(2,3)) 32, 33, 33
32 WRITE (6, 240) LCAP, CBH
GC TO 34
33 IF (CP23L - CAP(2,3)) 34, 34, 35
35 WRITE (6, 245) LCAP, CBL
34 CONTINUE

ZTOTAL(2,2) = ZTOTAL(4,1) + ZTWO
YTOTAL(2,2) = (1.0 / ZTOTAL(2,2)) + 1.0 / ZTHREE
ZTOTAL(2,1) = ZONE + (1.0 / YTOTAL(2,2))
WRITE (6, 280) ZTOTAL(2,1)

200 FORMAT ('0', 'DATA FOR TEE SECTION')
201 FORMAT ('0', '20A1')
202 FORMAT ('0', '19X, 'TO MATCH AN IMPEDANCE OF', F10.3, ' OHMS',
11X, 'TO AN IMPEDANCE OF', F10.3, ' OHMS', /)
210 FORMAT(1H0,20X, 16HEACH LEG WILL BE, F10.3, 6H OHMS, //, 21X,
17HLEG ONE, F10.3, 6H OHMS, 7X, 'COIL ONE', F10.3, ' UHENRY')
220 FORMAT(1H0,20X, 7HLEG TWO, F10.3, 6H OHMS, 7X, 'COIL TWO',
F10.3, 6H UHENRY)
230 FORMAT(1H0,20X, 9HLEG THREE, F10.3, 6H OHMS, 7X,
17HLEG FOUR, F10.3, 6H UHENRY)
240 FORMAT (1H0, 20X, 'CAP', I3, 2X, 'TOO HIGH MAX VALUE IS',
F10.3, ' UFD')
245 FORMAT (1H0, 20X, 'CAP', I3, 2X, 'TOO LOW MIN VALUE IS', 7X,
F10.3, ' UFD')
250 FORMAT (1H0, 20X, 'COIL', I3, 2X, 'TOO HIGH MAX VALUE IS',
F10.3, ' UHENRY')
255 FORMAT (1H0, 20X, 'COIL', I3, 2X, 'TOO LOW MIN VALUE IS',
F10.3, ' UHENRY')
280 FORMAT(1H0, 20X, 12HINPUT TO TEE, 2G10.3, 6H OHMS)

RETURN
END

SUBROUTINE RESIST (VCOIL, VQ, MASK)

THIS SUBROUTINE WILL DETERMINE THE EFFECT OF
THE BANDWIDTH RESISTOR SYSTEM AS THE SERIES

```

101 C COIL IS VARIED FROM MINIMUM TO MAXIMUM VALUE.
102 C
103 C VCOIL IS ANY DESIRED VALUE FOR THE BANDWIDTH
104 C RESISTOR COIL, AND VQ THE RESULTING Q OF THE
105 C CIRCUIT. IF THE MINIMUM AND MAXIMUM VALUES OF
106 C THE COIL SETTING ARE DESIRED, SET VCOIL = 0.0.
107 C
108 C IF MASK = 0 NO PRINTOUT
109 C MASK = 1 PRINT OUT RESULTS
110 C
111 C
112 C COMPLEX S, XC(5,3), XL(5,3), XTOTAL(5,2), YTOTAL(5,2),
113 1ZTOTAL(5,2), ZT, AMPS(5,3), VOLTS(5,3), POWER(5,2),
114 2ZCNE, ZTWO, ZTHREE
115 C
116 C COMMON/A/ COIL(5,3), CAP(5,3), RAS, RDC, RAD, RBW, PI
117 C COMMON/D/ TOWER, SELRES, WATTS, QNOW, PRBW, PRBKW, PWRKW
118 C COMMON/E/ VOLTS, AMPS, XC, XL, XTOTAL, YTOTAL, ZTOTAL
119 C COMMON/G/ CENFCY, OMEGA, S
120 C COMMON/H/ EA, EC, ED, EE, EF, EG, FQ, RBWCL, RBWCH
121 C COMMON/Z/ IBAR(120)
122 C
123 C IF ( VCOIL ) 4,4,5
124 C
125 4 CCIL(3,1) = RBWCL
126 GO TO 6
127 5 CCIL(3,1) = VCOIL
128 C
129 6 QS = CABS ( XTOTAL(4,2) ) / RAS
130 RP = FACT1(QS) * RAS
131 C
132 XTOTAL(4,1) = FACT2(QS) * XTOTAL(4,2)
133 1 XL(3,1) = S * CCIL(3,1)
134 QBWP = CABS ( XL(3,1) ) / RBW
135 BWRP = FACT1( QBWP ) * RBW
136 C
137 GP = (1.0/BWRP) + (1.0 / RP)
138 QP = 1.0 / ( CABS( XTOTAL(4,1) ) * GP )
139 RS = 1. / (FACT1(QP) * GP )
140 VQ = CABS ( XC(5,1) ) / RS
141 IF ( COIL(3,1) - RBWCL ) 2,2,3
142 2 QMIN = CABS ( XC(5,1) ) / RS
143 CCIL(3,1) = RBWCH
144 GO TO 1
145 3 QMAX = CABS ( XC(5,1) ) / RS
146 DB = RBWCH * 1.0E6
147 DC = RBWCL * 1.0E6
148 C
149 IF ( MASK ) 7,7,8
150 8 WRITE (6,300)
151 WRITE(6,301) (IBAR(I), I = 1,27 )
152 WRITE (6,310) DB, QMAX, DC, QMIN
153 C
154 300 FORMAT(1H0, 27HDATA FOR BANDWIDTH RESISTOR)
155 301 FORMAT ( ' ', 30A1 )
156 310 FORMAT(1H0, 10X, 38HWITH BANDWIDTH RESISTOR THE Q MAY VARY, (//,
157 120X, 11HCOIL SET AT, F10.3, 8H UHENRY, 9H THE Q IS, F10.3) )
158 C
159 7 CONTINUE
160 RETURN
161 END
162 **

```

MINOR SUBPROGRAMS

SUBROUTINE MATRIX (CENFCY, MASK)

THIS SUBROUTINE WILL PUT THE VARIOUS "BLOCKS"
OF THE SYSTEM INTO AN "ABCD" MATRIX
FORMULATION, FOR USE IN MANIPULATION.

IF MASK = 0 NO PRINTOUT
MASK = 1 PRINT OUT MATRICES

COMPLEX S, XC(5,3), XL(5,3), XTOTAL(5,2), YTOTAL(5,2),
ZTOTAL(5,2), ZT, AMPS(5,3), VOLTS(5,3), POWER(5,2),
ZTCNE, ZTWO, ZTHREE

COMPLEX A(2,2), B(2,2), C(2,2), D(2,2), E(2,2), F(2,2), G(2,2),
H(2,2), P(2,2), R(2,2), T(2,2), U(2,2), V(2,2), W(2,2), X(2,2),
ZUU(2,2), VV(2,2), EP(2,2), RP(2,2), UP(2,2), WP(2,2)

COMPLEX ZTANK(4)

COMPLEX AA, BB, CC, DD, EE, FF

COMMON/AA/ COIL(5,3), CAP(5,3), RAS, ROC, RAD, RBW, PI

COMMON/AB/ CPL(4), PHASE(5,2), TAP(4), COILM(4)

COMMON/AC/ A, B, C, D, E, F, G, O, P, R, T, U, V, W, X, UU, VV

COMMON/AD/ DUM, ZLOAD, RPTP, QPRI(4), CAP1(4)

COMMON/AE/ EP, RP, UP, WP

COMMON/AF/ IBAR(120)

OMEGA = 2.0 * PI * CENFCY

S = CMPLX (0.0, OMEGA)

ZCNE = (S * CCIL(2,1))

ZTWO = (S * CCIL(2,2))

ZTHREE = (1.0 / (S * CAP(2,3)))

THIS IS MATRIX FOR ANTENNA

A(1,1) = (S * CCIL(5,1) + 1.0 / (S * CAP(5,1) + RAO + RDC)) / RAD

A(1,2) = (0.0, 0.0)

A(2,1) = 1.0 / RAO

A(2,2) = (0.0, 0.0)

THIS IS MATRIX FOR HELIX HOUSE

B(1,1) = (1.0, 0.0)

B(1,2) = S * COIL(4,2)

B(2,1) = 1.0 / (S * COIL(4,1))

B(2,2) = ((S * COIL(4,1)) + (S * COIL(4,2))) / (S * COIL(4,1))

THIS IS MATRIX FOR BANDWIDTH RESISTOR

C(1,1) = (1.0, 0.0)

C(1,2) = (0.0, 0.0)

C(2,1) = 1.0 / (RBW + (S * COIL(3,1)))

C(2,2) = (1.0, 0.0)

THIS IS MATRIX FOR TEE NETWORK

D(1,1) = 1.0 + (ZONE / ZTHREE)

D(1,2) = ZONE + ZTWO + (ZONE * ZTWO) / ZTHREE

D(2,1) = 1.0 / ZTHREE

D(2,2) = 1.0 + (ZTWO / ZTHREE)

DC 7 L = 1.4

AA = COIL(1,1) / COILM(L)

EE = S * ((COIL(1,1) * TAP(L)) - (COILM(L)**2)) / COILM(L)

FF = 1.0 / (S * S * CAP1(L) * COILM(L) * L)

BB = ((AA) / (S * CAP1(L) * L)) + EE

CC = (AA * S * CAP1(L)) + (1.0 / (S * COILM(L)))

DD = (S * CAP1(L) * BB) + FF + (TAP(L) / COILM(L))

GO TO (3, 4, 5, 6), L

THIS IS MATRIX FOR 1 TANK CIRCUIT

3 E(1,1) = AA

E(1,2) = BB

E(2,1) = CC

E(2,2) = DD

THIS IS REVERSE MATRIX FOR 1 TANK CIRCUIT

F(1,1) = E(2,2)

F(1,2) = E(1,2)

F(2,1) = E(2,1)

F(2,2) = E(1,1)

GO TO 7

THIS IS MATRIX FOR 2 TANK CIRCUITS

4 R(1,1) = AA

R(1,2) = BB

R(2,1) = CC

R(2,2) = DD

THIS IS REVERSE MATRIX FOR 2 TANK CIRCUITS

T(1,1) = R(2,2)

T(1,2) = R(1,2)

T(2,1) = R(2,1)

T(2,2) = R(1,1)

GO TO 7

THIS IS MATRIX FOR 3 TANK CIRCUITS

5 U(1,1) = AA

U(1,2) = BB

U(2,1) = CC

U(2,2) = DD

```

10001 C      THIS IS REVERSE MATRIX FOR 3 TANK CIRCUITS
10002 V(1,1) = U(2,2)
10003 V(1,2) = U(1,2)
10004 V(2,1) = U(2,1)
10005 V(2,2) = U(1,1)
10006 GC TO 7
10007 C      THIS IS MATRIX FOR 4 TANK CIRCUITS
10008 W(1,1) = AA
10009 W(1,2) = AR
10010 W(2,1) = CC
10011 W(2,2) = CD
10012 C      THIS IS REVERSE MATRIX FOR 4 TANK CIRCUITS
10013 X(1,1) = W(2,2)
10014 X(1,2) = W(1,2)
10015 X(2,1) = W(2,1)
10016 X(2,2) = W(1,1)
10017 7 CONTINUE
10018 C
10019 C      THIS IS REVERSE MATRIX FOR THE TEE NETWORK
10020 G(1,1) = D(2,2)
10021 G(1,2) = D(1,2)
10022 G(2,1) = D(2,1)
10023 G(2,2) = D(1,1)
10024 C      THIS IS REVERSE MATRIX FOR HELIX HOUSE
10025 O(1,1) = R(2,2)
10026 O(1,2) = R(1,2)
10027 O(2,1) = R(2,1)
10028 O(2,2) = R(1,1)
10029 C      THIS IS THE REVERSE MATRIX FOR THE ANTENNA
10030 P(1,1) = A(2,2)
10031 P(1,2) = RAO
10032 P(2,1) = A(1,2)
10033 P(2,2) = (1.C.O.O)
10034 C
10035 C
10036 IF ( MASK 1, 2, 2, 1
10037 1 WRITE (6,7000)
10038 WRITE (6,7001) (IPAR(I), I = 1,29 )
10039 WRITE (6,700)
10040 WRITE (6,701) ( (A(I,J), J=1,2), I=1,2)
10041 WRITE (6,710)
10042 WRITE (6,701) ( (P(I,J), J=1,2), I=1,2)
10043 WRITE (6,720)
10044 WRITE (6,701) ( (C(I,J), J=1,2), I=1,2)
10045 WRITE (6,730)
10046 WRITE (6,701) ( (D(I,J), J=1,2), I=1,2)
10047 WRITE (6,740)
10048 WRITE (6,701) ( (E(I,J), J=1,2), I=1,2)
10049 WRITE (6,741)
10050 WRITE (6,701) ( (R(I,J), J=1,2), I=1,2)
10051 WRITE (6,742)
10052 WRITE (6,701) ( (U(I,J), J=1,2), I=1,2)
10053 WRITE (6,743)
10054 WRITE (6,701) ( (W(I,J), J=1,2), I=1,2)
10055 WRITE (6,750)
10056 WRITE (6,701) ( (F(I,J), J=1,2), I=1,2)
10057 WRITE (6,751)
10058 WRITE (6,701) ( (T(I,J), J=1,2), I=1,2)
10059 WRITE (6,752)
10060 WRITE (6,701) ( (V(I,J), J=1,2), I=1,2)
10061 WRITE (6,753)
10062 WRITE (6,701) ( (X(I,J), J=1,2), I=1,2)
10063 WRITE (6,760)
10064 WRITE (6,701) ( (G(I,J), J=1,2), I=1,2)
10065 WRITE (6,770)
10066 WRITE (6,701) ( (O(I,J), J=1,2), I=1,2)
10067 WRITE (6,780)
10068 WRITE (6,701) ( (P(I,J), J=1,2), I=1,2)
10069 C
10070 7000 FORMAT ( '1', 'MATRICES FOR CIRCUIT ELEMENTS' )
10071 7001 FORMAT ( '0', 30A1, '/' )
10072 700 FORMAT ( '0', 10X, 'MATRIX (A) FOR ANTENNA CIRCUIT' )
10073 701 FORMAT ( '(1H), /, 20X, 2(2G15.5) ) )
10074 710 FORMAT ( '0', 10X, 'MATRIX (B) FOR HELIX CIRCUIT' )
10075 720 FORMAT ( '0', 10X, 'MATRIX (C) FOR BANDWIDTH RESISTOR' )
10076 730 FORMAT ( '0', 10X, 'MATRIX (D) FOR TEE NETWORK' )
10077 740 FORMAT ( '0', 10X, 'MATRIX (E) FOR 1 TANK CIRCUIT' )
10078 741 FORMAT ( '0', 10X, 'MATRIX (R) FOR 2 TANK CIRCUITS' )
10079 742 FORMAT ( '0', 10X, 'MATRIX (U) FOR 3 TANK CIRCUITS' )
10080 743 FORMAT ( '0', 10X, 'MATRIX (W) FOR 4 TANK CIRCUITS' )
10081 750 FORMAT ( '0', 10X, 'MATRIX (F) FOR 1 REVERSE TANK' )
10082 751 FORMAT ( '0', 10X, 'MATRIX (T) FOR 2 REVERSE TANKS' )
10083 752 FORMAT ( '0', 10X, 'MATRIX (V) FOR 3 REVERSE TANKS' )
10084 753 FORMAT ( '0', 10X, 'MATRIX (X) FOR 4 REVERSE TANKS' )
10085 760 FORMAT ( '0', 10X, 'MATRIX (G) FOR REVERSE TEE' )
10086 770 FORMAT ( '0', 10X, 'MATRIX (O) FOR REVERSE HELIX' )
10087 780 FORMAT ( '0', 10X, 'MATRIX (P) FOR REVERSE ANTENNA' )
10088 2 CONTINUE
10089 C
10090 RETURN
10091 END
10092
10093 SUBROUTINE EVARY ( MASK )
10094 C
10095 C      THIS SUBROUTINE WILL DETERMINE THE Q AND
10096 C      BANDWIDTH FOR THE ANTENNA ALONE ( QA & BWA )
10097 C      AND WITH THE LOSS RESISTANCE INCLUDED ( QL & BWL ).

```

```

C
C      IF MASK = 0 NO PRINTOUT
C      MASK = 1 PRINT OUT RESULTS
C
COMMON/A/ COIL(5,3), CAP(5,3), RAS, RDC, RAD, RBW, PI
COMMON/O/ QVFREQ(41), QVQA(41), QVOL(41), QVBWA(41), QVBWL(41)
C
DC 1C L = 1.41
CYCLES = 1E4 + (L - 1) * 5E2
QVFREQ(L) = (1.E-3) * CYCLES
OMEGA = 2. * PI * CYCLES
QVQA(L) = 1.0 / ( OMEGA * CAP(5,1) * RAD )
QVOL(L) = 1.0 / ( OMEGA * CAP(5,1) * RAS )
QVBWA(L) = CYCLES / QVQA(L)
QVBWL(L) = CYCLES / QVOL(L)
10 CONTINUE
C
IF ( MASK - 1 ) 99, 1, 99
1 WRITE (6,100)
WRITE (6,200)
WRITE (6,300)
DC 2 L = 1.41, 2
WRITE(6,400) QVFREQ(L), QVQA(L), QVBWA(L), QVOL(L), QVBWL(L)
2 CONTINUE
99 CONTINUE
C
100 FORMAT(1H0, '//, 20X, 'VARIATION OF Q AND BANDWIDTH ',
1'WITH FREQUENCY', // )
200 FORMAT ( 1H0, 9X, 'FREQUENCY', 25X, 'ANTENNA ALONE',
120X, 'WITH LOSS' )
300 FORMAT ( 12X, 'KHZ', 33X, 'Q', 3X, 'BANDWIDTH', 15X,
1'Q', 3X, 'BANDWIDTH' )
400 FORMAT ( 1H0, 5X, F10.1, 25X, 2(F10.3), 10X, 2(F10.3) )
C
RETURN
END

```



```

1 23 XFMR4(L) = 1. / YTOTAL(1,1)
C
12 CONTINUE
C
99 CONTINUE
C
GC TC ( 4, 5, 6, 5 ) . MASK
5 WRITE (6,500)
WRITE (6,601) (IPAR(I), I = 1,116)
WRITE (6,605)
WRITE (6,715) (IPAR(I), I=1,95 )
WRITE (6,710)
WRITE (6,725)
WRITE (6,730)
WRITE (6,735) (IPAR(I), I = 1,110)
DC 7 L=1,K
IF ( L - KK ) 15, 14, 13
13 IF ( L - KK - 1 ) 15, 14, 15
14 WRITE (6,800) (IPAR(I), I = 1,116)
15 WRITE (6,740) FREQ(L), ZTEE(L), ZRES(L), ZHELIX(L), ZANT(L)
7 CONTINUE
WRITE (6,735) (IPAR(I), I = 1,110)
C
IF ( MASK - 3 ) 4, 6, 6
6 WRITE (6,700)
WRITE (6,601) (IPAR(I), I = 1,116)
WRITE (6,710)
WRITE (6,715) (IPAR(I), I=1,95 )
WRITE (6,720)
WRITE (6,725)
WRITE (6,730)
WRITE (6,735) (IPAR(I), I = 1,110)
DC 8 L=1,K
IF ( L - KK ) 17, 17, 16
16 IF ( L - KK - 1 ) 18, 17, 18
17 WRITE (6,800) (IPAR(I), I = 1,116)
18 WRITE (6,740) FREQ(L), XFMR1(L), XFMR2(L), XFMR3(L), XFMR4(L)
8 CONTINUE
WRITE (6,735) (IPAR(I), I = 1,110)
C
4 CONTINUE
C
500 FORMAT ( '1', 20X, 'VARIATION IN NETWORK IMPEDANCES AS A ',
1' FUNCTION OF FREQUENCY')
601 FORMAT (1H0, 116A1 )
605 FORMAT ( 1X, '1', 5X, 'FREQUENCY', 4X, '1', 29X,
1' INPLT IMPEDANCE TO VARIOUS STAGES', 33X, '1' )
610 FORMAT ( 1X, '1', 6X, 'HERTZ', 6X, '1', 10X, 'TEE', 10X, '1', 7X,
1' RESISTOR', 8X, '1', 9X, 'HELIX', 9X, '1', 9X, 'AERIAL', 8X, '1' )
700 FORMAT ( '1', 20X, 'VARIATION IN POWER AMPLIFIER IMPEDANCES',
1' AS A FUNCTION OF FREQUENCY')
710 FORMAT ( 1X, '1', 5X, 'FREQUENCY', 4X, '1', 30X,
1' NUMBR OF AMPLIFIERS ON THE LINE', 33X, '1' )
715 FORMAT ( 1X, '1', 18X, '1', 95A1, '1' )
720 FORMAT ( 1X, '1', 6X, 'HERTZ', 6X, '1', 10X, 'ONE', 10X, '1', 10X,
1' TWO', 10X, '1', 9X, 'THREE', 9X, '1', 10X, 'FOUR', 9X, '1', 10X,
725 FORMAT ( 1X, '1', 18X, '1', 23X, '1', 23X, '1', 23X, '1', 23X, '1' )
730 FORMAT ( 1X, '1', 18X, '1', 4( 5X, 'R', 8X, 'JX', 7X, '1' ) )
735 FORMAT ( 1X, '1', 18A1, '1', 23A1, '1', 23A1, '1', 23A1, '1', 23A1,
1' )
740 FORMAT ( 'X', '1', 4X, F10.3, 4X, '1', 4( 1X, 2G11.4, '1' ) )
800 FORMAT ( '+', 116A1 )
C
RETURN
END

```



```

101 C
102 IF ( HK ) 23, 23, 22
103 22 CALL MULT ( C, UU, VV, 2, 2, 2, 1 )
104 VOLT(4,1) = VV(1,1)
105
106 C
107 23 CURTWR(L) = VOLT(4,1) / ZTWR(L)
108 CURHEL(L) = VOLT(4,1) / ZHELIX(L)
109 CALL MULT ( C, VV, WW, 2, 2, 2, 1 )
110 VOLT(5,1) = WW(1,1)
111 CURANT(L) = VOLT(5,1) / ZANT(L)
112 CALL MULT ( C, WW, UU, 2, 2, 2, 1 )
113 VOLT(5,2) = UU(1,1)
114 CURRAD(L) = VOLT(5,2) / RAD
115 PWROUT(L) = VOLT(5,2) * CONJG( CURRAD(L) )
116
117 C
118 10 CONTINUE
119
120 C
121 GO TO ( 4, 5, 6, 5 ) , MASK
122 5 WRITE(6,500) MDOF
123 WRITE(6,601) (IRAR(I), I = 1,116)
124 WRITE(6,605)
125 WRITE(6,715) (IRAR(I), I=1,95 )
126 WRITE(6,610)
127 WRITE(6,725)
128 WRITE(6,730)
129 WRITE(6,735) (IRAR(I), I = 1,110)
130 DO 7 I=1,K
131 IF ( L - KK ) 15, 14, 13
132 IF ( L - KK - 1 ) 15, 14, 15
133 13 WRITE(6,800) (IRAR(I), I = 1,116)
134 14 WRITE(6,740) FREQ(L), CURX (L), CURTEE(L), CURRES(L), CURHEL(L)
135 7 CONTINUE
136 WRITE(6,735) (IRAR(I), I= 1,110)
137
138 C
139 IF ( MASK - 3 ) 4, 6, 6
140 6 WRITE(6,500) MDOF
141 WRITE(6,601) (IRAR(I), I = 1,116)
142 WRITE(6,605)
143 WRITE(6,715) (IRAR(I), I=1,95 )
144 WRITE(6,720)
145 WRITE(6,725)
146 WRITE(6,730)
147 WRITE(6,735) (IRAR(I), I = 1,110)
148 DO 8 I=1,K
149 IF ( L - KK ) 19, 17, 16
150 IF ( L - KK - 1 ) 18, 17, 18
151 16 WRITE(6,900) (IRAR(I), I = 1,116)
152 17 WRITE(6,740) FREQ(L), CURTWR(L), CURANT(L), CURRAD(L), PWROUT(L)
153 8 CONTINUE
154 WRITE(6,735) (IRAR(I), I = 1,110)
155
156 C
157 4 CONTINUE
158
159 C
160 500 FORMAT ( '1', 20X, 'VARIATION IN CURRENTS AS A FUNCTION OF ',
161 '1'FREQUENCY (USING', 11, ' TRANSFORMERS' )
162 601 FORMAT (1H0, 116A1 )
163 605 FORMAT ( 1X, '1', 5X, 'FREQUENCY', 4X, '1', 20X,
164 '1'COMPLEX CURRENTS IN AMPERES', 1117, '1' )
165 610 FORMAT ( 1X, '1', 6X, 'HERTZ', 6X, '1', 6X, 'TRANSFORMER', 6X, '1',
166 '11CX, 'TEF', 12X, '1', 7X,
167 '2'RESISTOR', 9X, '1', 9X, 'HELIX', 9X, '1' )
168 715 FORMAT ( 1X, '1', 18X, '1', 95A1, '1' )
169 720 FORMAT ( 1X, '1', 6X, 'HERTZ', 6X, '1', 8X, 'ANTENNA', 8X, '1',
170 '18X, 'AERIAL', 9X, '1', 2X, 'THRU RADIATION LOAD', 2X, '1',
171 '22X, 'POWER OUT IN WATTS', 3X, '1' )
172 725 FORMAT ( 1X, '1', 18X, '1', 23X, '1', 23X, '1', 23X, '1', 23X, '1', 23X, '1' )
173 730 FORMAT ( 1X, '1', 18X, '1', 4( 5X, 'R', 8X, 'J', 7X, '1' ) )
174 735 FORMAT ( 1X, '1', 18A1, '1', 23A1, '1', 23A1, '1', 23A1, '1', 23A1,
175 '1' )
176 740 FORMAT ( 1X, '1', 4X, F10.3, 4X, '1', 4( 1X, 2G11.4, '1' ) )
177 800 FORMAT ( '1', 116A1 )
178
179 C
180 RETURN
181 END

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SUBROUTINE GRAPH (K, MODE, ITYPE)

THIS SUBROUTINE WILL TAKE THE TABULAR DATA DEVELOPED BY SUBROUTINE DELTA AND PREPARE IT FOR GRAPHICAL PRESENTATION. IT WILL THEN MAKE THE NECESSARY CALLS FOR THE GRAPHS. MODE IS A CONTROL USED TO DETERMINE THE TYPE OF GRAPHS TO BE USED.

IF MODE=1 USE THE PLOT GRAPH
 IF MODE=2 USE THE PLOTIT GRAPH
 IF MODE=3 USE BOTH TYPES OF GRAPHS

IF ITYPE=1 GRAPH THE IMPEDANCES
 IF ITYPE=2 GRAPH THE CURRENTS

COMPLEX S, XC(5,3), XL(5,3), XTOTAL(5,2), VTOTAL(5,2),
 IZTOTAL(5,2), ZT, AMPS(5,3), VOLTS(5,3), POWER(5,2),
 ZONE, ZTWO, ZTHREE
 COMPLEX PRIMRY, TOP, BOTTOM, XFMR1(241), XFMR2(241),
 XFMR3(241), XFMR4(241), ZANT(241), ZTWR(241), ZHELIX(241),
 ZRES(241), ZTEE(241)
 COMPLEX CURANT(241), CURTWR(241), CURHEL(241), CURRES(241),
 CURTEE(241), CURX1(241), CURX2(241), CURX3(241), CURX4(241)
 COMPLEX CURPAD(241), PWROUT(241)

DIMENSION ALPHA (241), BETA (241), GAMMA (241), EATA (241)
 DIMENSION EPSI(241), PSI(241)
 DIMENSION Y1(1), Y2(1), Y3(1), Y4(1), Y5(1), Y6(1), Y7(1),
 Y8(1), Y9(1)
 DIMENSION TITLE1(1), TITLE2(1), TITLE3(1), TITLE4(1), TITLE5(1)

COMMON/H/ FA, FC, FD, EE, EF, EG, FO, RBWCL, RBWCH
 COMMON/J/ FREQ(241), DIV(241), ZANT, ZHELIX, ZRES, ZTEE, ZTWR
 COMMON/K/ XFMR1, XFMR2, XFMR3, XFMR4
 COMMON/L/ CURANT, CURTWR, CURHEL, CURRES, CURTEE
 COMMON/M/ CURX1, CURX2, CURX3, CURX4
 COMMON/N/ CURPAD, PWROUT
 COMMON/S/ ALPHA, BETA, GAMMA, EATA, EPSI, PSI

GO TO (3, 4), ITYPE

3 WRITE (6,199) FO
 DO 1 INDEX = 1,K
 ALPHA(INDEX) = REAL (ZHELIX(INDEX))
 BETA(INDEX) = AIMAG(ZHELIX(INDEX))
 GAMMA(INDEX) = REAL (ZTEE(INDEX))
 EATA(INDEX) = AIMAG(ZTEE(INDEX))
 1 CONTINUE

GO TO (50, 53, 50), MODE

50 CONTINUE
 WRITE(6,205)
 CALL PTPLOT (DIV, ALPHA, K, ' FREQ-KHZ HELIX-R ')
 CALL PTPLOT (DIV, BETA, K, ' FREQ-KHZ HELIX-JX ')
 WRITE(6,206)
 CALL PTPLOT (DIV, GAMMA, K, ' FREQ-KHZ TEE -R ')
 CALL PTPLOT (DIV, EATA, K, ' FREQ-KHZ TEE -JX ')
 WRITE(6,207)
 CALL PTPLOT (DIV, GAMMA, K, ' FREQ-KHZ TEE -R ')
 CALL PTPLOT (DIV, EATA, K, ' FREQ-KHZ TEE -JX ')
 WRITE(6,208)
 CALL PTPLOT (DIV, GAMMA, K, ' FREQ-KHZ TEE -R ')
 CALL PTPLOT (DIV, EATA, K, ' FREQ-KHZ TEE -JX ')

51 IF (MODE - 1) 52, 52, 53

53 CONTINUE
 WRITE(6,200)
 CALL PLOTIT (K, G, DIV, ALPHA, BETA, Y3, Y4,
 Y5, Y6, Y7, Y8, Y9, K, 1, 1, 1, 1, 1, 1, 1,
 2'RESISTIVE HELIX IMPEDANCE FREQ-HZ
 3'REACTIVE HELIX IMPEDANCE
 4'TITLE3, TITLE4, TITLE5)
 WRITE (6,201)
 CALL PLOTIT (K, G, DIV, GAMMA, EATA, Y3, Y4,
 Y5, Y6, Y7, Y8, Y9, K, 1, 1, 1, 1, 1, 1, 1,
 2'RESISTIVE TEE IMPEDANCE FREQ-HZ
 3'REACTIVE TEE IMPEDANCE
 4'TITLE3, TITLE4, TITLE5)

GO TO 52

4 WRITE (6,199) FO
 DO 2 INDEX = 1,K
 ALPHA(INDEX) = REAL (CURTWR(INDEX))
 BETA(INDEX) = AIMAG(CURTWR(INDEX))
 GAMMA(INDEX) = REAL (CURTEE(INDEX))
 EATA(INDEX) = AIMAG(CURTEE(INDEX))
 EPSI(INDEX) = REAL (CURX1(INDEX))
 PSI(INDEX) = AIMAG(CURX1(INDEX))
 2 CONTINUE

GO TO (60, 63, 61), MODE

60 CONTINUE
 WRITE(6,405)
 CALL PTPLOT (DIV, ALPHA, K, ' FREQ-KHZ AMPS-R ')
 CALL PTPLOT (DIV, BETA, K, ' FREQ-KHZ AMPS-J ')
 WRITE(6,406)
 CALL PTPLOT (DIV, GAMMA, K, ' FREQ-KHZ AMPS-R ')
 CALL PTPLOT (DIV, EATA, K, ' FREQ-KHZ AMPS-J ')
 WRITE(6,407)
 CALL PTPLOT (DIV, GAMMA, K, ' FREQ-KHZ AMPS-R ')
 CALL PTPLOT (DIV, EATA, K, ' FREQ-KHZ AMPS-J ')
 WRITE(6,408)
 CALL PTPLOT (DIV, GAMMA, K, ' FREQ-KHZ AMPS-R ')
 CALL PTPLOT (DIV, EATA, K, ' FREQ-KHZ AMPS-J ')

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      CALL PTPLOT ( DIV, EATA, K, * FREQ-KHZ - AMPS-J )
C
61 IF I MODE = 1 1 52, 52, 63
C
63 CONTINUE
  WRITE(6,400)
  CALL PLOTIT ( K, 0, DIV, ALPHA, BETA, Y3, Y4,
    Y5, Y6, Y7, YR, YQ, K, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1 )
  2*ANTENNA CURRENT - REAL FREQ-HZ
  3*ANTENNA CURRENT - IMAG
  4*TITLE3, TITLE4, TITLE5
  WRITE(6,411)
  CALL PLOTIT ( K, 0, DIV, GAMMA, EATA, Y3, Y4,
    Y5, Y6, Y7, YR, YQ, K, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1 )
  2*TEE CURRENT - REAL FREQ-HZ
  3*TEE CURRENT - IMAG
  4*TITLE3, TITLE4, TITLE5
C
52 CONTINUE
C
109 FORMAT ( '0', 2X, 'THE FOLLOWING GRAPHS WILL PRESENT THE ABOVE',
  1' TABULAR DATA, CENTERED AT', F10.3, ' KHZ' )
203 FORMAT ( '1', 3X, 'VARIATION IN COMPLEX HELIX',
  1' IMPEDANCE VERSUS FREQUENCY' )
201 FORMAT ( '1', 3X, 'VARIATION IN COMPLEX TEE',
  1' IMPEDANCE VERSUS FREQUENCY' )
205 FORMAT ( '1', 3X, 'HELIX RESISTANCE VERSUS FREQUENCY' )
206 FORMAT ( '1', 3X, 'HELIX REACTANCE VERSUS FREQUENCY' )
207 FORMAT ( '1', 3X, 'TEE RESISTANCE VERSUS FREQUENCY' )
208 FORMAT ( '1', 3X, 'TEE REACTANCE VERSUS FREQUENCY' )
403 FORMAT ( '1', 3X, 'VARIATION IN ANTENNA CURRENT VERSUS',
  1' FREQUENCY' )
401 FORMAT ( '1', 3X, 'VARIATION IN TEE CURRENT VERSUS FREQUENCY' )
405 FORMAT ( '1', 3X, 'ANTENNA CURRENT (REAL) VERSUS FREQUENCY' )
406 FORMAT ( '1', 3X, 'ANTENNA CURRENT (IMAG) VERSUS FREQUENCY' )
407 FORMAT ( '1', 3X, 'TEE CURRENT (REAL) VERSUS FREQUENCY' )
408 FORMAT ( '1', 3X, 'TEE CURRENT (IMAG) VERSUS FREQUENCY' )
409 FORMAT ( '1', 3X, 'POWER RADIATED (REAL) VERSUS FREQUENCY' )
410 FORMAT ( '1', 3X, 'POWER RADIATED (IMAG) VERSUS FREQUENCY' )
  RETURN
  END
C
SUBROUTINE ABCD
C
      THIS SUBROUTINE WILL MADE USE OF THE
      ABCD MATRICES FOR THE VARIOUS TRANSFORMERS USED.
C
  COMPLEX S, XC(5,3), XL(5,3), XTOTAL(5,2), YTOTAL(5,2),
  1ZTOTAL(5,2), ZT, AMPS(5,3), VOLTS(5,3), POWER(5,2),
  2ZONE, ZTWO, ZTHREE
  COMPLEX A(2,2), B(2,2), C(2,2), D(2,2), F(2,2), G(2,2),
  1H(2,2), P(2,2), R(2,2), T(2,2), U(2,2), V(2,2), W(2,2), X(2,2),
  2UU(2,2), VV(2,2), FP(2,2), RP(2,2), UP(2,2), WP(2,2), WW(2,2)
  COMPLEX XX(2,2)
C
  COMMON/R/ C(14), PHASE(5,2), TAP(4), COILM(4)
  COMMON/V/ VOLTS, AMPS, XC, XL, XTOTAL, YTOTAL, ZTOTAL
  COMMON/G/ GENFCY, OMEGA, S
  COMMON/N/ A, B, C, D, E, F, G, H, P, R, T, U, V, W, X, UU, VV
  COMMON/Q/ FP, RP, UP, WP
  COMMON/W/ TRAP(120)
C
  UU(1,1) = VOLTS(5,2)
  UU(2,1) = - AMPS(5,2)
C
  CALL MATRIX ( GENFCY, 0 )
C
  CALL MULT ( A, UU, VV, 2, 2, 2, 1 )
  VOLTS(5,1) = VV(1,1)
  AMPS(5,1) = VV(2,1)
  CALL MULT ( B, VV, UU, 2, 2, 2, 1 )
  VOLTS(4,1) = UU(1,1)
  AMPS(4,1) = UU(2,1)
  VV(1,1) = UU(1,1)
  VV(2,1) = UU(2,1)
  UU(3,1) = VV(1,1)
  AMPS(3,1) = VV(2,1)
  CALL MULT ( C, VV, UU, 2, 2, 2, 1 )
  VOLTS(2,1) = UU(1,1)
  AMPS(2,1) = UU(2,1)
  VV(1,1) = UU(1,1)
  VV(2,1) = UU(2,1)
C
  WRITE(6, 801)
  WRITE(6, 802) (I=1,120)
  WRITE(6, 803)
  WRITE(6, 804)
C
  I = 5
  II = 2
  CALL COMP ( VOLTS, AMPS, ZTOTAL, PHASE, POWER, I, 2 )
  WRITE(6, 910) 1, II, VOLTS(I,2), AMPS(I,2), ZTOTAL(I,2),
  1PHASE(I,2), POWER(I,2)
C
  IF 77 II = 1,4
  IF 80 II = 1
  IF 81 II = 1

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227 CALL COMP ( VOLTS, AMPS, ZTOTAL, PHASE, POWER, I, II )
228 WRITE (6, P11) I, II, VOLTS(1,1), AMPS(1,1), ZTOTAL(1,1),
229 1PHASE(1,1), POWER(1,1)
230 777 CONTINUE
231
232 C THIS SECTION IS FOR ONE POWER AMPLIFIER
233 C
234 WRITE (6, P15)
235 CALL MHLT ( F, VV, FP, 2, 2, 2, 1 )
236 VOLTS(1,1) = FP(1,1)
237 AMPS(1,1) = FP(2,1)
238 CALL COMP ( VOLTS, AMPS, ZTOTAL, PHASE, POWER, 1, 1 )
239 I = 1
240 WRITE (6, P11) I, VOLTS(1,1), AMPS(1,1), ZTOTAL(1,1),
241 1PHASE(1,1), POWER(1,1)
242
243 C THIS SECTION IS FOR TWO POWER AMPLIFIERS
244 C
245 VV(1,1) = UH(1,1) / 2
246 CALL MHLT ( R, VV, RP, 2, 2, 2, 1 )
247 VOLTS(1,1) = RP(1,1)
248 AMPS(1,1) = RP(2,1)
249 CALL COMP ( VOLTS, AMPS, ZTOTAL, PHASE, POWER, 1, 1 )
250 I = 2
251 WRITE (6, P11) I, VOLTS(1,1), AMPS(1,1), ZTOTAL(1,1),
252 1PHASE(1,1), POWER(1,1)
253
254 C THIS SECTION IS FOR THREE POWER AMPLIFIERS
255 C
256 VV(1,1) = UH(1,1) / 3
257 CALL MHLT ( U, VV, UP, 2, 2, 2, 1 )
258 VOLTS(1,1) = UP(1,1)
259 AMPS(1,1) = UP(2,1)
260 CALL COMP ( VOLTS, AMPS, ZTOTAL, PHASE, POWER, 1, 1 )
261 I = 3
262 WRITE (6, P11) I, VOLTS(1,1), AMPS(1,1), ZTOTAL(1,1),
263 1PHASE(1,1), POWER(1,1)
264
265 C THIS SECTION IS FOR FOUR POWER AMPLIFIERS
266 C
267 VV(1,1) = UH(1,1) / 4
268 CALL MHLT ( W, VV, WP, 2, 2, 2, 1 )
269 VOLTS(1,1) = WP(1,1)
270 AMPS(1,1) = WP(2,1)
271 CALL COMP ( VOLTS, AMPS, ZTOTAL, PHASE, POWER, 1, 1 )
272 I = 4
273 WRITE (6, P11) I, VOLTS(1,1), AMPS(1,1), ZTOTAL(1,1),
274 1PHASE(1,1), POWER(1,1)
275
276 C
277 RC) FORMAT ( '1', 2X, 'THE FOLLOWING ARE VOLTAGE AND CURRENT '
278 1'COMPUTATIONS USING THE ABCD MATRICES', // )
279 PC1) FORMAT ( '01', 1X, 'VOLTAGE ACROSS AND CURRENT THROUGH THE ',
280 1'RADIATION RESISTANCE ARE USED FOR REFERENCE', // )
281 PC2) FORMAT ( '01', 119A1 )
282 PC5) FORMAT ( 1H0, 1X, 4HTERM, 10X, 5HVOLTS, 22X,
283 14HAMPS, 12X, 9HIMPEDANCE, 10X, 5HDPHASE, 11X, 5HPOWER )
284 PC1) FORMAT (1H0, 2X, 11, 1H., 11, 3(2G13.3), F8.2, 2G13.3)
285 PC11) FORMAT (1H0, 2X, 11, 2X, 3(2G13.3), F8.2, 2G13.3)
286 PC15) FORMAT ( '1', 1X, 'FOLLOWING ARE PLATE-TO-PLATE VALUES WITH',
287 1' DIFFERENT POWER AMPLIFIERS', //, 2X, 'TANKS' )
288
289 C
290 RETURN
291 END
292
293

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ACCESSORY SUBPROGRAMS

BLOCK DATA

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COMMON/A/ COIL(5,3), CAP(5,3), RAS, RDC, RAD, RBW, PI
COMMON/R/ CPL(4), PHASE(5,2), TAP(4), COILM(4)
COMMON/D/ TOWER, SELRES, WATTS, QNOW, PRBW, PRBWKW, PWRKW
COMMON/E/ CP21H, CP21L, CP23H, CP23L, CL21H, CL21L, CL22H, CL22L
COMMON/G/ CENFCY, OMEGA, S
COMMON/H/ EA, EC, ED, EE, EF, EG, FQ, RBWCL, RBWCH
COMMON/P/ DUM, ZLOAD, RPTP, QPRI(4), CAP(4)
COMMON/Z/ IBAR(120)
DATA CP21H, CP23H, CL21H, CL22H/1.5E-6, 6.6E-7, 2.75E-6, 3.00E-6/
DATA CP21L, CP23L, CL21L, CL22L/4.0E-8, 6.0E-8, 25.0E-6, 50.0E-6/
DATA CPL/ 0.522, 0.474, 0.444, 0.508/
DATA RBWCL, RBWCH/ 2.0E-4, 8.0E-4/
DATA TAP/ 71.5E-6, 49.0E-6, 35.3E-6, 27.0E-6/
DATA PI, WATTS, RBW, PRBW/3.1415926, 1.0E6, 33.25, 5.0E5/
DATA COIL(1,1), CAP(1,1)/ 430.0E-6, 0.25E-6/
COMPLEX ZLOAD/ (20.0, 0.0) /
DATA RPTP /420.0/
DATA CENFCY, TOWER, RAD, RAS/15.5E3, 628.0, 0.154, 0.308/
DATA CAP(5,1), COIL(5,1)/ 0.164E-6, 139.0E-6/
DATA DUM, IBAR/ 0.0, 120*PI /
END

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FUNCTION FACT1 (A)

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FACT1 = ( A ** 2 ) + 1.0
RETURN
END

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FUNCTION FACT2 (R)

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FACT2 = ( ( R**2 ) + 1.0 ) / ( B ** 2 )
RETURN
END

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SUBROUTINE MULT (XRAY, YOKE, ZERRA, K, L, M, N)

THIS SUBROUTINE WILL MULTIPLY TWO MATRICES, XRAY TIMES YOKE,
OF ORDER (K X L) AND (M X N), RESPECTIVELY, GIVING A PRODUCT
MATRIX ZERRA OF ORDER (K X N).

```

COMPLEX XRAY, YOKE, ZERRA
DIMENSION XRAY(K,L), YOKE(M,N), ZERRA(K,N)
IF (K - 9) 5, 10, 10
IF (L - 9) 15, 10, 10
IF (M - 9) 20, 10, 10
IF (N - 9) 25, 10, 10
10 WRITE ( 6, 400 )
GO TO 99
25 IF (K - 1) 30, 35, 35
35 IF (L - 1) 30, 40, 40
40 IF (M - 1) 30, 45, 45
45 IF (N - 1) 30, 50, 50
50 WRITE ( 6, 500 )
GO TO 99
50 IF (L - M) 55, 60, 55
55 WRITE ( 6, 600 )
GO TO 99
60 DO 99 IX = 1, K
DO 99 JX = 1, N
ZERRA(IX,JX) = (0.0,0.0)
DO 99 KX = 1, M
ZERRA(IX,JX) = (XRAY(IX,KX) * YOKE(KX,JX)) + ZERRA(IX,JX)
99 CONTINUE

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400 FORMAT (37HMATRIX INVALID. ORDER GREATER THAN 8.)
500 FORMAT (34HMATRIX INVALID. ORDER LESS THAN 1.)
600 FORMAT (36HMATRIX INVALID. ORDERS DO NOT AGREE.)

RETURN

END

SUBROUTINE COMP (V, A, Z, PHI, PWR, L, LL)

THIS SUBROUTINE WILL COMPUTE THE IMPEDANCE, PHASE ANGLE
(USING CURRENT AS REFERENCE), AND POWER FOR THE GIVEN COMPLEX
VOLTAGE (V) AND COMPLEX CURRENT (A).

```

DIMENSION V(L,LL), A(L,LL), Z(L,LL), PHI(L,LL), PWR(L,LL)
COMPLEX V, A, Z, PWR

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```

PI = 3.1415926536
IF ( CAHS ( A(L,LL) ) ) 1,2,1
2 WRITE ( 6, 10 ) L,LL
GO TO 9
1 IF ( CAHS ( V(L,LL) ) ) 1,3,4,3
4 WRITE ( 6, 11 ) L,LL
GO TO 9
3 RA = REAL ( A(L,1) )
GA = AIMAG ( A(L,1) )

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101 RV = REAL ( V(L,LL) )
102 GV = AIMAG ( V(L,LL) )
103 Z(L,LL) = V(L,LL) / A(L,LL)
104 PWR(LL,LL) = V(L,LL) * CONJG ( A(L,LL) )
105 PHI(LL,LL) = ( ATAN2(GV,RV) - ATAN2(GA,RA) ) * (180.0/PI)
106 9 CONTINUE
107 C
108 10 FORMAT(1H0,9X,5HAMPS(, 12, 2H .. 12, 10H ) IS ZERO )
109 11 FORMAT(1H0,9X,6HVOLTS(, 12, 2H .. 12, 10H ) IS ZERO )
110 C
111 RETURN
112 END
113
114
115 SUBROUTINE PIPILOT ( X, Y, K, TITLE )
116 C
117 C
118 C
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THIS SUBROUTINE WILL PLOT UP TO 9 DEPENDENT ARRAYS, Y1 THRU Y9, AGAINST THE INDEPENDENT VARIABLE "X", ON THE PAGE PRINTER. THE NO. OF POINTS IN THE X ARRAY WILL DETERMINE THE NUMBER OF LINES ON BOTH THE X-AXIS AND Y-AXIS WILL BE PRINTED IF THEY ARE IN THE R THE GRAPH. THE MAIN PROGRAM MUST BE DIMENSIONED WITH THE DUMMY VARIABLES Y1(1) THRU Y9(1) AND TITLE(1) THRU TITLE5(1). THESE VARIABLES WILL BE USED WHEN LESS THAN 9 CURVES ARE TO BE PRINTED SEE EXAMPLE BELOW. THE X-ARRAY MAY BE SORTED INTO ASCENDING OR IF NECESSARY OR DESIRED BY THE USER BY CALLING KK. THE PRODUCT OF THE NUMBER OF CURVES PLOTTED (PLUS 1) AND THE NUMBER OF POINTS - EACH CURVE MUST BE LESS THAN OR EQUAL TO 1000. FOR EXAMPLE, WITH 9 CURVES OF 250 POINTS EACH, WILL HAVE, $(3+1) * (250) = 1000$. FOR 9 CURVES A MAXIMUM OF 100 POINTS MAY BE USED IN EACH. TITLING FOR THE CURVES WILL BE DONE THROUGH THE USE OF TITLE1 THROUGH TITLE5. EACH CURVE NAME MAY BE UP TO 28 CHARACTERS LONG. TITLE USE THE FIRST 28 SPACES FOR THE NAME OF CURVE #1, THE NEXT 12 FOR THE NAME OF THE "X" ARRAY. NAMES FOR THE FOLLOWING 8 CURVES PLACED 2 TO A CARD, IN SEQUENCE, USING TITLE2 THRU TITLE5.

```

K= NUMBER OF POINTS IN X-ARRAY
IF KK=1 THE X-ARRAY WILL BE PUT INTO ASCENDING ORDER
KK=1 THE X-ARRAY WILL BE PRINTED AS GIVEN
Y1-YO THE DUMMY ARRAYS FOR THE 9 CURVES
IA-IA THE DUMMY DIMENSIONS FOR CURVES Y2 THRU Y9

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CALL PLOTIT ( 250, 1, A, B, C, D, Y4, Y5, Y6, Y7, Y8, Y9,
1250, 250, 250, 1, 1, 1, 1, 1,
2*FIRST 28 SPACES TITLE OF B..NEXT 12 FOR A TITLE.....,
3*FIRST 28 SPACES TITLE OF C..NEXT 28 SPACES FOR D.....,
4*TITLE3, TITLE4, TITLE5 )
```

```
COMMON/77 LARK(120)
INTEGER NAME( 70), TITLE1(14), TITLE2(14), TITLE3(14),
1 TITLE4(14), TITLE5(14)
```

```

TOTAL = K + IA + IR + IC + ID + IE + IF + IG + IH
IF ( TOTAL - 100 ) 1, 1, 2
WRITE ( 6, 50 )
GO TO 99

```

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1  NO = 3
   IF ( ( IH.FO.1 ) ) NO = 8
   IF ( ( IG.FO.1 ) ) NO = 7
   IF ( ( IF.FO.1 ) ) NO = 6
   IF ( ( IE.FO.1 ) ) NO = 5
   IF ( ( ID.FO.1 ) ) NO = 4
   IF ( ( IC.FO.1 ) ) NO = 3
   IF ( ( IB.FO.1 ) ) NO = 2
   IF ( ( IA.FO.1 ) ) NO = 1
   LIMIT = NO + 1

```

KA	=	1001
KB	=	1001
KC	=	1001
KD	=	1001
KE	=	1001
KF	=	1001
KG	=	1001
KH	=	1001
LA	=	1
LB	=	1
LC	=	1
LD	=	1
LE	=	1
LF	=	1
LG	=	1
LH	=	1

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101      8 KF = L + 6*K
102      LF = L + 5*K
103      7 KD = L + 5*K
104      LD = L + 4*K
105      6 KC = L + 4*K
106      LC = L + 3*K
107      5 KR = L + 3*K
108      LR = L + 2*K
109      4 KA = L + 2*K
110      LA = L
111      3 A(L) = X(L)
112      A(L+K) = Y1(L)
113      A(KA) = Y2(LA)
114      A(KR) = Y3(LR)
115      A(KC) = Y4(LC)
116      A(KD) = Y5(LD)
117      A(KF) = Y6(LF)
118      A(KF) = Y7(LF)
119      A(KG) = Y8(LG)
120      12 A(KH) = Y9(LH)
121
122      C
123      IF ( KK ) 13, 142, 13
124      13 DO 141 II = 1, K
125      JJ = II + 1
126      DO 141 I = JJ, K
127      IF ( A(II) - A(I) ) 141, 141, 15
128      15 NN = -K
129      DO 140 N = 1, LIMIT
130      NN = NN + K
131      F = A(II+NN)
132      A(II+NN) = A(I+NN)
133      A(I+NN) = F
134      140 CONTINUE
135      141 CONTINUE
136      142 CONTINUE
137
138      C
139      C
140      C
141      C
142      C
143      C
144      ISIGN(1) = IPLUS
145      ISIGN(2) = ISTAR
146      ISIGN(3) = ISQUIG
147      ISIGN(4) = ITITAT
148      ISIGN(5) = IPER
149      ISIGN(6) = ISIX
150      ISIGN(7) = ISEVEN
151      ISIGN(8) = IATF
152      ISIGN(9) = ININE
153
154      C
155      C
156      M = K + 1
157      MM = (LIMIT * K
158      BIG = A(M)
159      SMALL = A(M)
160
161      C
162      DO 16 JIM = 1, MM
163      IF ( BIG - A(JIM) ) 17, 18, 18
164      17 BIG = A(JIM)
165      GO TO 16
166      18 IF ( SMALL - A(JIM) ) 16, 16, 19
167      19 SMALL = A(JIM)
168      16 CONTINUE
169
170      C
171      SPAN = BIG - SMALL
172      IF ( SPAN ) 20, 21, 22
173      21 WRITE ( 6, 100 )
174      GO TO 20
175      20 WRITE ( 6, 200 ) ( LARK(I), I = 1, 115 )
176
177      C
178      C
179      DO 60 L = 1, 14
180      NAME(L) = TITLE1(L)
181      NAME(L+14) = TITLE2(L)
182      NAME(L+28) = TITLE3(L)
183      NAME(L+42) = TITLE4(L)
184      NAME(L+56) = TITLE5(L)
185
186      C
187      WRITE ( 6, 250 ) ( NAME(I), I = 1, 7 ), ISIGN(1), ( NAME(I), I = 8, 10 )
188
189      C
190      N = 15
191      NN = 21
192      DO 61 L = 2, NN
193      WRITE ( 6, 255 ) ( NAME(I), I = N, NN ), ISIGN(L)
194      N = N + 7
195      NN = NN + 7
196      61 CONTINUE
197
198      C
199      C
200      WRITE ( 6, 600 ) ( LARK(I), I = 1, 112 )
201
202      C
203      IF ( SMALL ) 25, 26, 26
204      25 IF ( BIG ) 26, 27, 27
205      27 IYAXIS = ( ( ABS(SMALL) ) / SPAN ) * 99.0 + 1.0
206      GO TO 28
207      26 IYAXIS = 0
208      28 CONTINUE

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201 I
202 C
203 IXAXIS = 0
204 DO 22 J = 1, K
205 JJ = 0
206 J2 = J + 1
207 DO 24 ICLFAR = 1, 100
208 MARK(ICLFAR) = BLANK
209 C
210 IF ( IXAXIS ) 29, 30, 29
211 20 MARK(IXAXIS) = ICFAR
212 30 CONTINUE
213 C
214 IF ( IXAXIS - J ) 31, 32, 31
215 31 IF ( A(J) ) 33, 32, 34
216 33 IF ( A(J2) ) 35, 36, 37
217 34 IF ( A(J2) ) 37, 36, 35
218 37 IF ( ARS( X(I) ) - ARS( X(J2) ) ) 32, 32, 36
219 DO 34 J3 = 1, 100
220 MARK(J3) = ICFAR
221 GO TO 30
222 36 IXAXIS = J2
223 GO TO 39
224 35 IXAXIS = 0
225 39 CONTINUE
226 C
227 DO 23 JAY = 1, N0
228 JJ = JJ + 1
229 LY = ( ( A(JJ+1) - SMALL) / SPAN ) * 99.0 + 1.0
230 MARK(LY) = ISIGN(JAY)
231 23 CONTINUE
232 WRITE ( 6, 200 ) MARK, A(J)
233 A(K+1) = A(K)
234 22 CONTINUE
235 C
236 WRITE(6,600) (MARK(I), I = 1, 112 )
237 C
238 DEL = SPAN / 4.0
239 YPRINT( 1 ) = SMALL
240 YPRINT( 5 ) = BIG
241 DO 62 I = 2, 4
242 YPRINT(I) = SMALL + DEL*(I - 1)
243 C
244 WRITE(6,700)
245 WRITE(6,750) YPRINT
246 C
247 69 CONTINUE
248 50 FORMAT ( 1H1, //, 20X, 'NO PLOT SINCE LIMIT EXCEEDED' )
249 100 FORMAT ( 1H0, 'NO GRAPH SINCE SPAN = 0' )
250 200 FORMAT ( 115A1 )
251 250 FORMAT ( 1X, ' ', 20X, 7A4, ' PLOTTED WITH', 2X, 1A1, 36X,
252 1' ', 3A4, ' ' )
253 255 FORMAT ( 1X, ' ', 20X, 7A4, ' PLOTTED WITH', 2X, 1A1, 36X,
254 1' ', 12X, ' ' )
255 300 FORMAT ( 1X, ' ', 100A1, ' ', F12.2, ' ' )
256 600 FORMAT ( 1X, ' ', 100A1, ' ', 12A1, ' ' )
257 700 FORMAT ( ' +', ' ', 4( 24X, ' ' ) )
258 750 FORMAT ( 1X, G10.3, 1 X, G10.3, 3( 15X, G10.3 ) )
259 C
260 RETURN
261 END

```

OUTPUT DATA FOR THE VLF ANTENNA AT NORTHWEST CAPE

THESE ARE THE BASIC ANTENNA SYSTEM PARAMETERS

MAJOR PARAMETERS

CENTER FREQUENCY 15.525 KHZ
POWER RADIATED 1000.000 KW

FEED CIRCUIT

RADIATION RESISTANCE 0.142 OHMS
LOSS RESISTANCE 0.044 OHMS
TOP-HAT CAPACITANCE 0.164 UFARAD
DOWN-LEAD INDUCTANCE 139.000 UHENRY

BANDWIDTH RESISTOR CIRCUIT

RESISTANCE 33.250 OHMS
MAXIMUM DISSIPATION 500.000 KW
COIL TUNES FROM 200.000 TO 800.000 UHENRY

LC NETWORK

	MINIMUM	MAXIMUM
CAP CNF	0.360	0.600 UFARAD
COIL ONE	25.000	275.000 UHENRY
COIL TWO	50.000	300.000 UHENRY

PAIR CIRCUIT

EACH PRIMARY HAS INDUCTANCE OF 430.000 UHENRY
PRIMARY TUNING CAPACITOR 0.250 UFARAD
SECONDARY CAPACITOR TUNES 0.040 TO 1.500 UFARAD
NO. OF POWER AMPS ONE TWO THREE FOUR
EACH SECONDARY (UHENRY) 71.50 49.00 35.30 27.00
COUPLING COEFFICIENT 0.522 0.474 0.444 0.508
PLATE-TO-PLATE RESISTANCE 420.000 OHMS

THE FOLLOWING DATA IS COMPILED FOR THE ANTENNA AT RESONANCE

DATA FOR ANTENNA

ANTENNA SELF-RESONANCE	33.334 HERTZ	OPERATING FREQUENCY	15.525 KHZ
RADIATION RESISTANCE	0.142 OHMS	TOTAL REACTANCE	48.950 OHMS
C (AERIAL)	440.207	BANDWIDTH (30B)	35.268 HERTZ
LOSS RESISTANCE	0.044 OHMS	EFFICIENCY	76.344 PER-CENT
C (WITH LOSSES)	336.072	BANDWIDTH (30B)	46.195 HERTZ
POWER RADIATED	1000.000 KILOWATTS	CURRENT	2653.725 AMPS
TOP-HAT VOLTAGE	165.993 KV	BASE VOLTAGE	129.901 KV
VOLTS ACROSS RAC	376.229 VOLTS	VOLTS ACROSS R(LOSS)	116.764 VOLTS

DATA FOR FEED CIRCUIT

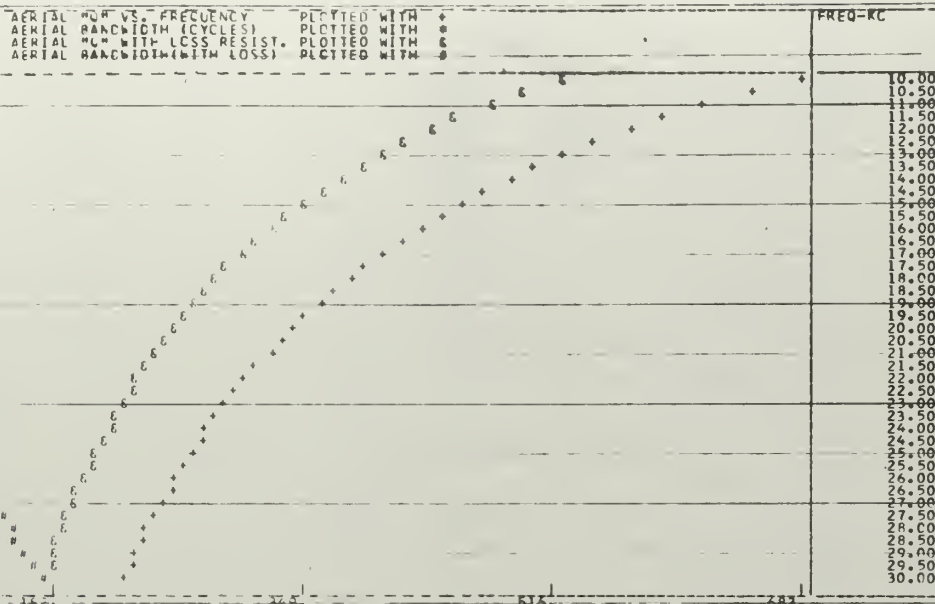
DESIRED OUTPUT IMPEDANCE	12.500 OHMS
SERIES COIL	496.302 UHENRY
COUPLING COIL	15.749 UHENRY
AT RESONANCE INPUT IMPEDANCE	12.500 - 12549E-03 OHMS

DATA FOR BANDWIDTH RESISTOR

WITH BANDWIDTH RESISTOR THE Q MAY VARY

COIL SET AT 500.000 UHENRY THE Q IS	318.282
COIL SET AT 200.000 UHENRY THE Q IS	265.117

VARIATION IN Q AND BANDWIDTH FOR AERIAL WITH AND WITHOUT LOSS RESISTANCE



DATA FOR THE SECTION

TO MATCH AN IMPEDANCE OF 20,000 OHMS TO AN IMPEDANCE OF 12,500 OHMS

EACH LEG WILL BE 15.811 OHMS

LEG ONE 15.811 OHMS COIL ONE 162.091 UHENRY

LEG TWO 15.811 OHMS COIL TWO 162.091 UHENRY

LEG THREE 15.811 OHMS CAP ONE 0.648 UFD

CAP 1 TCC HIGH MAX VALUE IS 0.600 UFD

INPUT TO TEE 20.0 0.194E-03 OHMS

DATA FOR TANK CIRCUIT

FOR EACH POWER AMPLIFIER- THE PRIMARY INDUCTANCE IS 430.000 UHENRY

PRIMARY CAPACITOR SET AT 0.244 UFARAD

THE DESIRED PLATE-TO-PLATE LOAD IS 420.000 OHMS

THE NETWORK LOAD IS 20.000 0.19264E-03 OHMS

FIG 1 POWER AMPLIFIERS

EACH SECONDARY INDUCTANCE IS 71.500 UHENRY

MUTUAL INDUCTANCE IS 91.529 UHENRY

COUPLING COEFFICIENT IS 0.522

SECONDARY CAPACITOR SET AT 1.470 UFARAD

LOAD SEEN BY SECONDARY 20.000 -6.9744 OHMS

PLATE-TO-PLATE LOAD IS 441.41 -41.939 OHMS

FIG 2 POWER AMPLIFIERS

EACH SECONDARY INDUCTANCE IS 49.000 UHENRY

MUTUAL INDUCTANCE IS 48.803 UHENRY

COUPLING COEFFICIENT IS 0.474

SECONDARY CAPACITOR SET AT 1.072 UFARAD

LOAD SEEN BY SECONDARY 9.999H -4.7797 OHMS

PLATE-TO-PLATE LOAD IS 390.58 -41.941 OHMS

FIG 3 POWER AMPLIFIERS

EACH SECONDARY INDUCTANCE IS 35.300 UHENRY

MUTUAL INDUCTANCE IS 54.702 UHENRY

COUPLING COEFFICIENT IS 0.444

SECONDARY CAPACITOR SET AT 0.992 UFARAD

LOAD SEEN BY SECONDARY 6.6666 -3.4433 OHMS

PLATE-TO-PLATE LOAD IS 411.94 -41.938 OHMS

FIG 4 POWER AMPLIFIERS

EACH SECONDARY INDUCTANCE IS 27.000 UHENRY

MUTUAL INDUCTANCE IS 54.737 UHENRY

COUPLING COEFFICIENT IS 0.508

SECONDARY CAPACITOR SET AT 0.973 UFARAD

LOAD SEEN BY SECONDARY 4.4444 -3.4337 OHMS

PLATE-TO-PLATE LOAD IS 404.96 -41.941 OHMS

MATRICES FOR CIRCUIT ELEMENTS

MATRIX (A) FOR ANTENNA CIRCUIT

1.3059	-344.72	0.0	0.0
7.0423	0.0	0.0	0.0

MATRIX (B) FOR HELIX CIRCUIT

1.0000	0.0	0.0	47.437
0.0	-0.65093	31.878	0.0

MATRIX (C) FOR BANDWIDTH RESISTOR

1.0000	0.0	0.0	0.0
0.46210E-02	-0.10845E-01	1.0000	0.0

MATRIX (D) FOR TEL NETWORK

0.47684E-06	0.0	0.0	15.811
0.0	0.63246E-01	0.47684E-06	0.0

MATRIX (E) FOR 1 TANK CIRCUIT

4.6580	0.0	0.0	23.838
0.0	0.33712E-07	0.21286	0.0

MATRIX (F) FOR 2 TANK CIRCUITS

3.1248	-0.38186E-06	0.33471E-07	0.68305
0.0	0.74707	0.16001	0.0

MATRIX (G) FOR 3 TANK CIRCUITS

2.6202	0.0	0.0	-1.1056
0.0	0.63489	0.12721	0.0

MATRIX (H) FOR 4 TANK CIRCUITS

1.5635	0.0	0.0	-1.2343
0.0	0.57318	0.12730	0.0

MATRIX (I) FOR 1 REVERSE TANK

0.21286	0.0	0.0	23.838
0.0	0.33712E-07	4.6580	0.0

MATRIX (J) FOR 2 REVERSE TANKS

0.32002	0.33471E-07	-0.38186E-06	1.3661
0.0	0.74707	3.1248	-0.38186E-06

MATRIX (K) FOR 3 REVERSE TANKS

0.38186	0.0	0.0	-3.3168
0.0	0.63489	2.6202	0.0

MATRIX (L) FOR 4 REVERSE TANKS

0.50918	0.0	0.0	-4.9371
0.0	0.57318	1.5635	0.0

MATRIX (M) FOR REVERSE TEL

0.47684E-06	0.0	0.0	15.811
0.0	0.63246E-01	0.47684E-06	0.0

MATRIX (N) FOR REVERSE HELIX

31.878	0.0	0.0	47.437
0.0	-0.65093	1.0000	0.0

MATRIX (P) FOR REVERSE ANTENNA

0.0	0.0	0.14200	0.0
0.0	0.0	1.0000	0.0

BT390.0

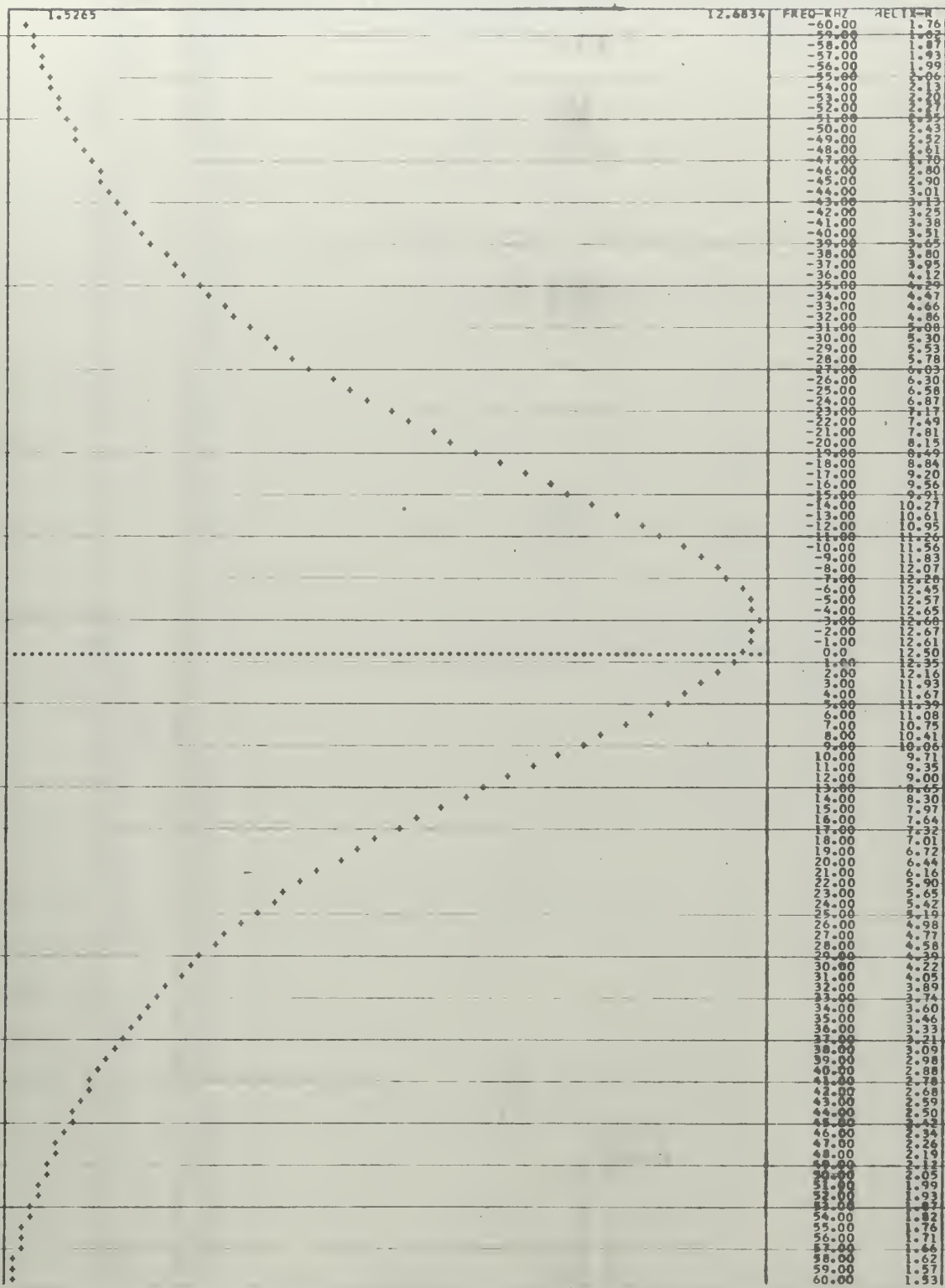
FOLLOWING ARE MATRIX PRODUCTS

TERM	VOLTS		AMPS		IMPEDANCE		PHASE	POWER	
5.2	392.	0.3	0.255E 04	0.0	0.154	0.0	-0.0	0.100E 07	0.0
5.1	785.	-0.125E 06	0.255E 04	0.0	0.308	-49.1	-89.64	0.200E 07	-0.919E 09
4.1	785.	-0.494E 04	62.8	-395.	12.5	-0.138E-03	-0.00	0.200E 07	-21.9
3.1	785.	-0.494E 04	62.8	-395.	12.5	-0.138E-03	-0.00	0.200E 07	-21.9
2.1	0.625E 04	993.	312.	40.6	20.0	0.227E-03	0.00	0.200E 07	22.7

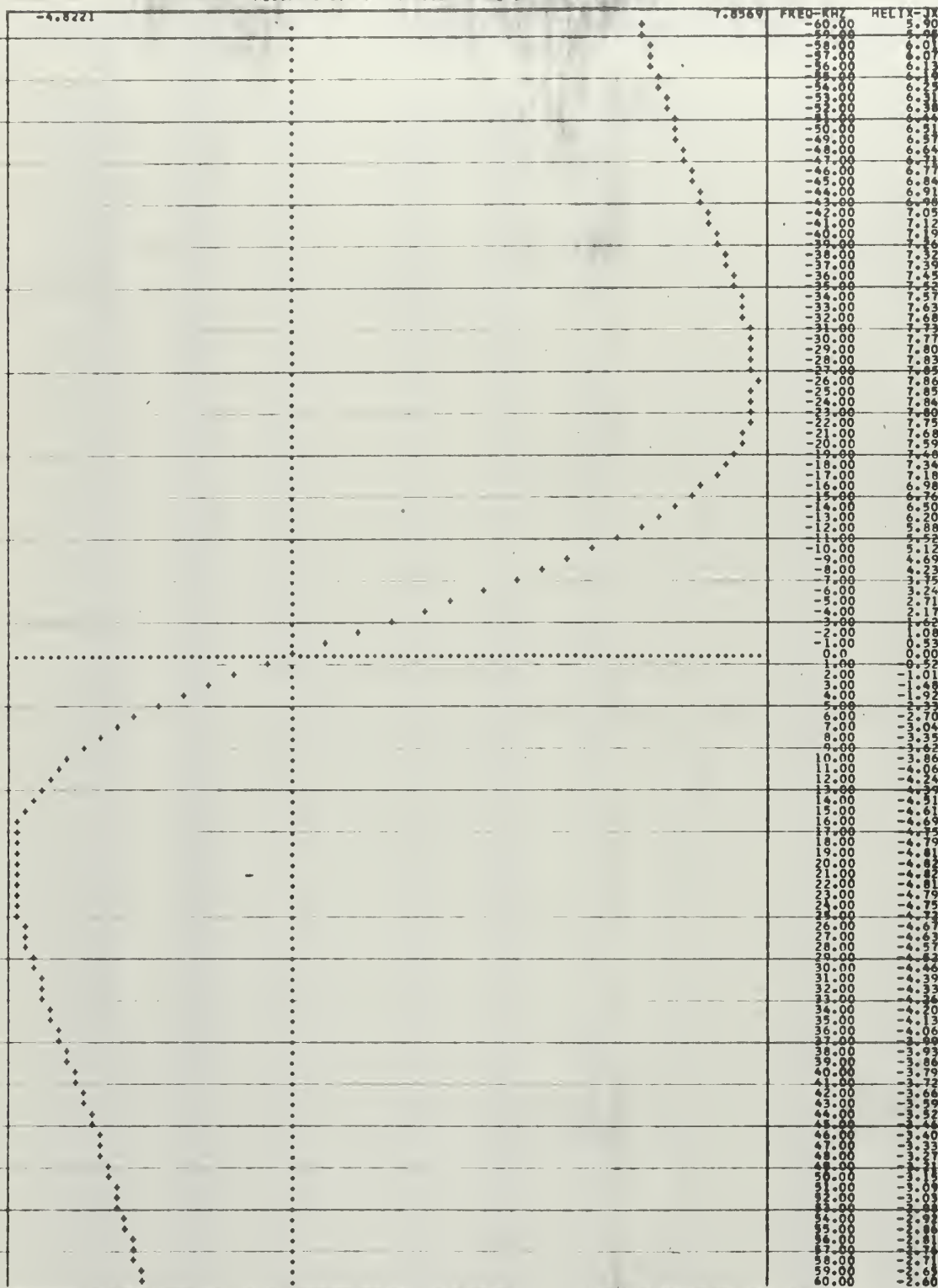
VARIATION IN NETWORK IMPEDANCES AS A FUNCTION OF FREQUENCY

FREQUENCY HERTZ	INPUT IMPEDANCE TO VARIOUS STAGES						AERIAL	
	TEE		RESISTOR		HELIX			
	R	JX	R	JX	R	JX	R	JX
15465.000	11.70	-40.30	1.408	5.372	1.761	5.897	0.1860	-49.25
15466.000	11.78	-39.76	1.451	5.283	1.813	5.953	0.1860	-49.24
15467.000	11.86	-39.21	1.497	5.194	1.865	6.011	0.1860	-49.24
15468.000	11.94	-38.67	1.544	5.105	1.917	6.069	0.1860	-49.23
15469.000	12.03	-38.12	1.594	5.016	1.969	6.129	0.1860	-49.23
15470.000	12.12	-37.57	1.645	4.927	2.021	6.189	0.1860	-49.23
15471.000	12.21	-37.01	1.700	4.838	2.073	6.250	0.1860	-49.22
15472.000	12.30	-36.46	1.756	4.749	2.125	6.313	0.1860	-49.21
15473.000	12.39	-35.90	1.813	4.660	2.177	6.376	0.1860	-49.21
15474.000	12.48	-35.35	1.877	4.571	2.229	6.440	0.1860	-49.20
15475.000	12.57	-34.79	1.942	4.482	2.281	6.506	0.1860	-49.20
15476.000	12.67	-34.24	2.010	4.393	2.333	6.572	0.1860	-49.19
15477.000	12.77	-33.68	2.081	4.304	2.385	6.638	0.1860	-49.19
15478.000	12.87	-33.04	2.155	4.215	2.437	6.706	0.1860	-49.18
15479.000	12.97	-32.46	2.234	4.126	2.489	6.774	0.1860	-49.18
15480.000	13.07	-31.88	2.316	4.037	2.541	6.843	0.1860	-49.17
15481.000	13.17	-31.29	2.402	3.948	2.593	6.912	0.1860	-49.17
15482.000	13.28	-30.70	2.493	3.859	2.645	6.981	0.1860	-49.16
15483.000	13.38	-30.11	2.588	3.770	2.697	7.050	0.1860	-49.16
15484.000	13.49	-29.51	2.687	3.681	2.749	7.120	0.1860	-49.15
15485.000	13.60	-28.91	2.790	3.592	2.801	7.188	0.1860	-49.15
15486.000	13.72	-28.30	2.903	3.503	2.853	7.257	0.1860	-49.14
15487.000	13.83	-27.70	3.017	3.414	2.905	7.323	0.1860	-49.14
15488.000	13.95	-27.08	3.140	3.325	2.957	7.389	0.1860	-49.13
15489.000	14.07	-26.47	3.267	3.236	3.009	7.453	0.1860	-49.13
15490.000	14.19	-25.86	3.403	3.147	3.061	7.515	0.1860	-49.12
15491.000	14.32	-25.23	3.543	3.058	3.113	7.574	0.1860	-49.12
15492.000	14.44	-24.60	3.693	2.969	3.165	7.636	0.1860	-49.11
15493.000	14.57	-23.97	3.848	2.880	3.217	7.698	0.1860	-49.11
15494.000	14.70	-23.33	4.014	2.791	3.269	7.759	0.1860	-49.10
15495.000	14.84	-22.69	4.186	2.702	3.321	7.819	0.1860	-49.10
15496.000	14.98	-22.04	4.369	2.613	3.373	7.879	0.1860	-49.09
15497.000	15.12	-21.39	4.560	2.524	3.425	7.938	0.1860	-49.09
15498.000	15.26	-20.74	4.759	2.435	3.477	7.997	0.1860	-49.08
15499.000	15.41	-20.07	4.970	2.346	3.529	8.055	0.1860	-49.08
15500.000	15.55	-19.41	5.190	2.257	3.581	8.113	0.1860	-49.07
15501.000	15.71	-18.74	5.421	2.168	3.633	8.172	0.1860	-49.07
15502.000	15.86	-18.07	5.660	2.079	3.685	8.230	0.1860	-49.06
15503.000	16.02	-17.39	5.912	1.990	3.737	8.288	0.1860	-49.06
15504.000	16.19	-16.71	6.177	1.901	3.789	8.346	0.1860	-49.05
15505.000	16.35	-16.01	6.444	1.812	3.841	8.404	0.1860	-49.05
15506.000	16.53	-15.32	6.723	1.723	3.893	8.462	0.1860	-49.04
15507.000	16.70	-14.62	7.014	1.634	3.945	8.520	0.1860	-49.04
15508.000	16.88	-13.91	7.309	1.545	4.000	8.578	0.1860	-49.03
15509.000	17.07	-13.20	7.615	1.456	4.052	8.636	0.1860	-49.03
15510.000	17.26	-12.48	7.925	1.367	4.104	8.694	0.1860	-49.02
15511.000	17.45	-11.75	8.241	1.278	4.156	8.752	0.1860	-49.02
15512.000	17.65	-11.01	8.559	1.189	4.208	8.810	0.1860	-49.01
15513.000	17.85	-10.28	8.874	1.100	4.260	8.868	0.1860	-49.01
15514.000	18.07	-9.525	9.189	1.011	4.312	8.926	0.1860	-49.00
15515.000	18.28	-8.772	9.496	0.922	4.364	8.984	0.1860	-49.00
15516.000	18.50	-8.002	9.797	0.833	4.416	9.042	0.1860	-48.99
15517.000	18.73	-7.233	10.08	0.744	4.468	9.100	0.1860	-48.99
15518.000	18.97	-6.464	10.35	0.655	4.520	9.158	0.1860	-48.98
15519.000	19.21	-5.695	10.60	0.566	4.572	9.216	0.1860	-48.98
15520.000	19.45	-4.882	10.83	0.477	4.624	9.274	0.1860	-48.97
15521.000	19.71	-4.040	11.03	0.388	4.676	9.332	0.1860	-48.97
15522.000	19.97	-3.212	11.20	0.299	4.728	9.390	0.1860	-48.97
15523.000	20.23	-2.380	11.35	0.210	4.780	9.448	0.1860	-48.96
15524.000	20.51	-1.523	11.48	0.121	4.832	9.506	0.1860	-48.96
15525.000	20.78	-0.663	11.59	0.032	4.884	9.564	0.1860	-48.95
15526.000	21.07	0.210	11.59	-0.057	4.936	9.622	0.1860	-48.95
15527.000	21.36	1.110	11.52	-0.146	4.988	9.680	0.1860	-48.94
15528.000	21.66	2.026	11.47	-0.235	5.040	9.738	0.1860	-48.94
15529.000	21.95	2.958	11.38	-0.324	5.092	9.796	0.1860	-48.93
15530.000	22.25	3.898	11.26	-0.413	5.144	9.854	0.1860	-48.93
15531.000	22.56	4.864	11.11	-0.502	5.196	9.912	0.1860	-48.92
15532.000	22.86	5.842	10.93	-0.591	5.248	9.970	0.1860	-48.92
15533.000	23.17	6.847	10.72	-0.680	5.300	10.028	0.1860	-48.91
15534.000	23.47	7.859	10.49	-0.769	5.352	10.086	0.1860	-48.91
15535.000	23.77	8.858	10.24	-0.858	5.404	10.144	0.1860	-48.90
15536.000	24.07	9.858	9.981	-0.947	5.456	10.202	0.1860	-48.90
15537.000	24.36	11.02	9.706	-1.036	5.508	10.260	0.1860	-48.89
15538.000	24.65	12.10	9.425	-1.125	5.560	10.318	0.1860	-48.89
15539.000	24.93	13.20	9.137	-1.214	5.612	10.376	0.1860	-48.88
15540.000	25.20	14.31	8.849	-1.303	5.664	10.434	0.1860	-48.88
15541.000	25.48	15.47	8.557	-1.392	5.716	10.492	0.1860	-48.87
15542.000	25.73	16.57	8.269	-1.481	5.768	10.550	0.1860	-48.87
15543.000	25.98	17.71	7.983	-1.570	5.820	10.608	0.1860	-48.86
15544.000	26.24	18.87	7.700	-1.659	5.872	10.666	0.1860	-48.86
15545.000	26.48	20.02	7.423	-1.748	5.924	10.724	0.1860	-48.85
15546.000	26.72	21.15	7.150	-1.837	5.976	10.782	0.1860	-48.85
15547.000	26.96	22.35	6.900	-1.926	6.028	10.840	0.1860	-48.84
15548.000	27.21	23.53	6.648	-2.015	6.080	10.898	0.1860	-48.84
15549.000	27.45	24.70	6.406	-2.104	6.132	10.956	0.1860	-48.83
15550.000	27.70	25.89	6.170	-2.193	6.184	11.014	0.1860	-48.83
15551.000	27.94	27.07	5.946	-2.282	6.236	11.072	0.1860	-48.82
15552.000	28.20	28.27	5.728	-2.371	6.288	11.130	0.1860	-48.82
15553.000	28.46	29.46	5.522	-2.460	6.340	11.188	0.1860	-48.81
15554.000	28.73	30.68	5.321	-2.549	6.392	11.246	0.1860	-48.81
15555.000	29.00	31.89	5.131	-2.638	6.444	11.304	0.1860	-48.80
15556.000	29.28	33.11	4.949	-2.727	6.496	11.362	0.1860	-48.80
15557.000	29.58	34.34	4.775	-2.816	6.548	11.420	0.1860	-48.79
15558.000	29.88	35.59	4.608	-2.905	6.600	11.478	0.1860	-48.79
15559.000	30.20	36.84	4.450	-2.994	6.652	11.536	0.1860	-48.78
15560.000	30.53	38.11	4.297	-3.083	6.704	11.594	0.1860	-48.78
15561.000	30.87	39.39	4.152	-3.172	6.756	11.652	0.1860	-48.77
15562.000	31.22	40.68	4.014	-3.261	6.808	11.710	0.1860	-48.77
15563.000	31.58	41.99	3.882	-3.350	6.860	11.768	0.1860	-48.76
15564.000	31.95	43.30	3.756	-3.439	6.912	11.826	0.1860	-48.76
15565.000	32.34	44.65	3.635	-3.528	6.964	11.884	0.1860	-48.75
15566.000	32.74	45.99	3.521	-3.617	7.016	11.942	0.1860	-48.75
15567.000	33.16	47.37	3.411	-3.706	7.068	12.000	0.1860	-48.75
15568.000	33.58	48.76	3.307	-3.795	7.120	12.058	0.1860	-48.74
15569.000	34.03	50.17	3.206	-3.884	7.172	12.116	0.1860	-48.74
15570.000	34.49	51.59	3.111	-3.973	7.224	12.174	0.1860	-48.73
15571.000	34.96	53.04	3.019	-4.062	7.276	12.232	0.1860	-48.73
15572.000	35.44	54.44	2.932	-4.151	7.328	12.290	0.1860	-48.72
15573.000	35.95	56.00	2.848	-4.240	7.380	12.348	0.1860	-48.72
15574.000	36.46	57.50	2.769	-4.329	7.432	12.406	0.1860	-48.71
15575.000	37.00	59.05	2.692	-4.418	7.484	12.464	0.1860	-48.71
15576.000	37.53	60.59	2.619	-4.507	7.536	12.522	0.1860	-48.70
15577.000	38.08	62.14	2.548	-4.596	7.588	12.580	0.1860	-48.70
15578.000	38.71	63.79	2.481	-4.685	7.640	12.638	0.1860	-48.69
15579.000	39.31	65.41	2.417	-4.774	7.692	12.696	0.1860	-48.69
15580.000	39.84	67.07	2.355	-4.863	7.744	12.754	0.1860	-48.68
15581.000	40.58	68.75	2.296	-4.952	7.796	12.812	0.1860	-48.68
15582.000	41.24	70.47	2.240	-5.041	7.848	12.870	0.1860	-48.67
15583.000	41.92	72.19	2.185	-5.130	7.900	12.928	0.1860	-48.67
15584.000	42.63	73.67	2.133	-5.219</				

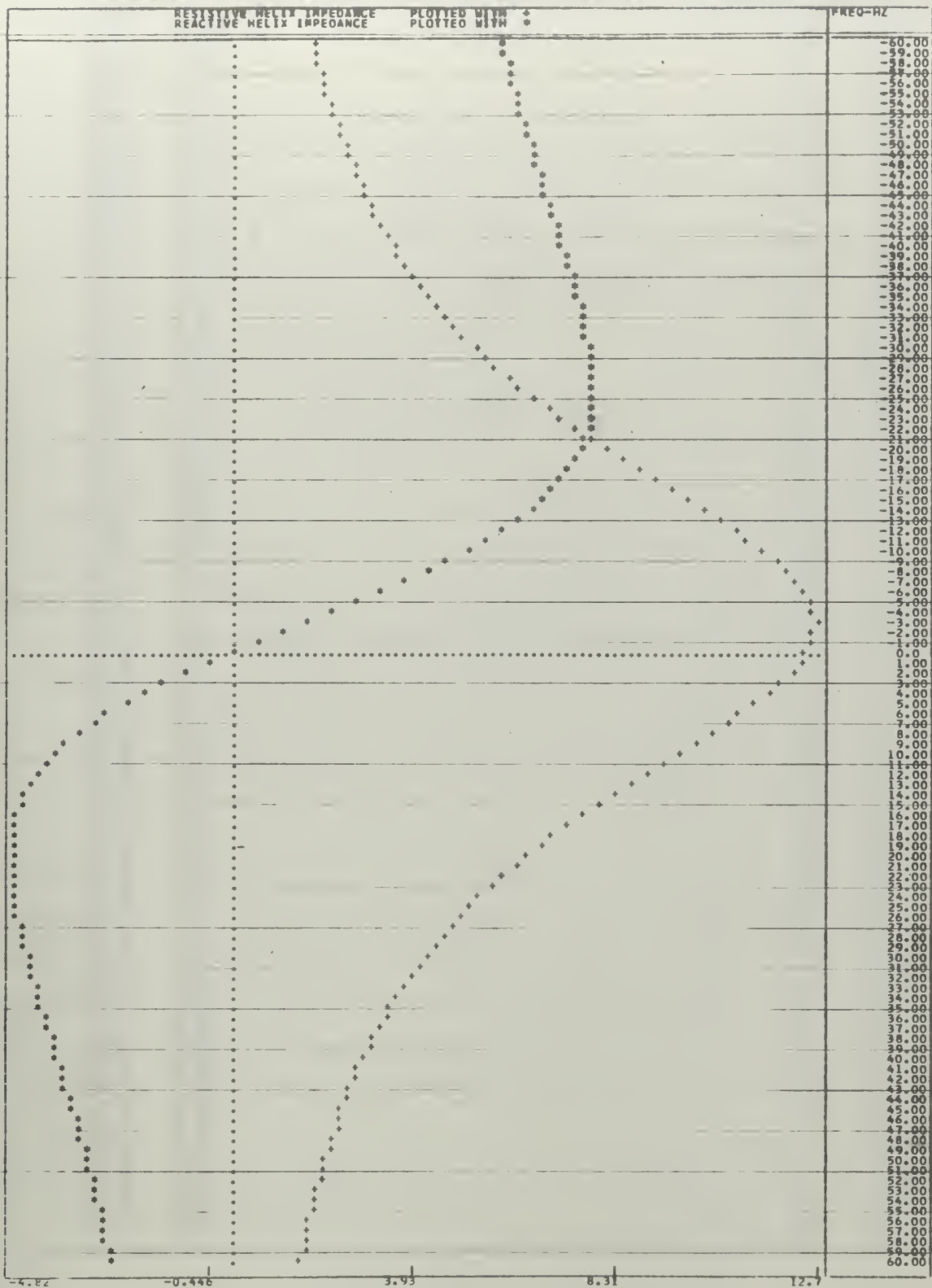
HELIX RESISTANCE VERSUS FREQUENCY



HELIX REACTANCE VERSUS FREQUENCY

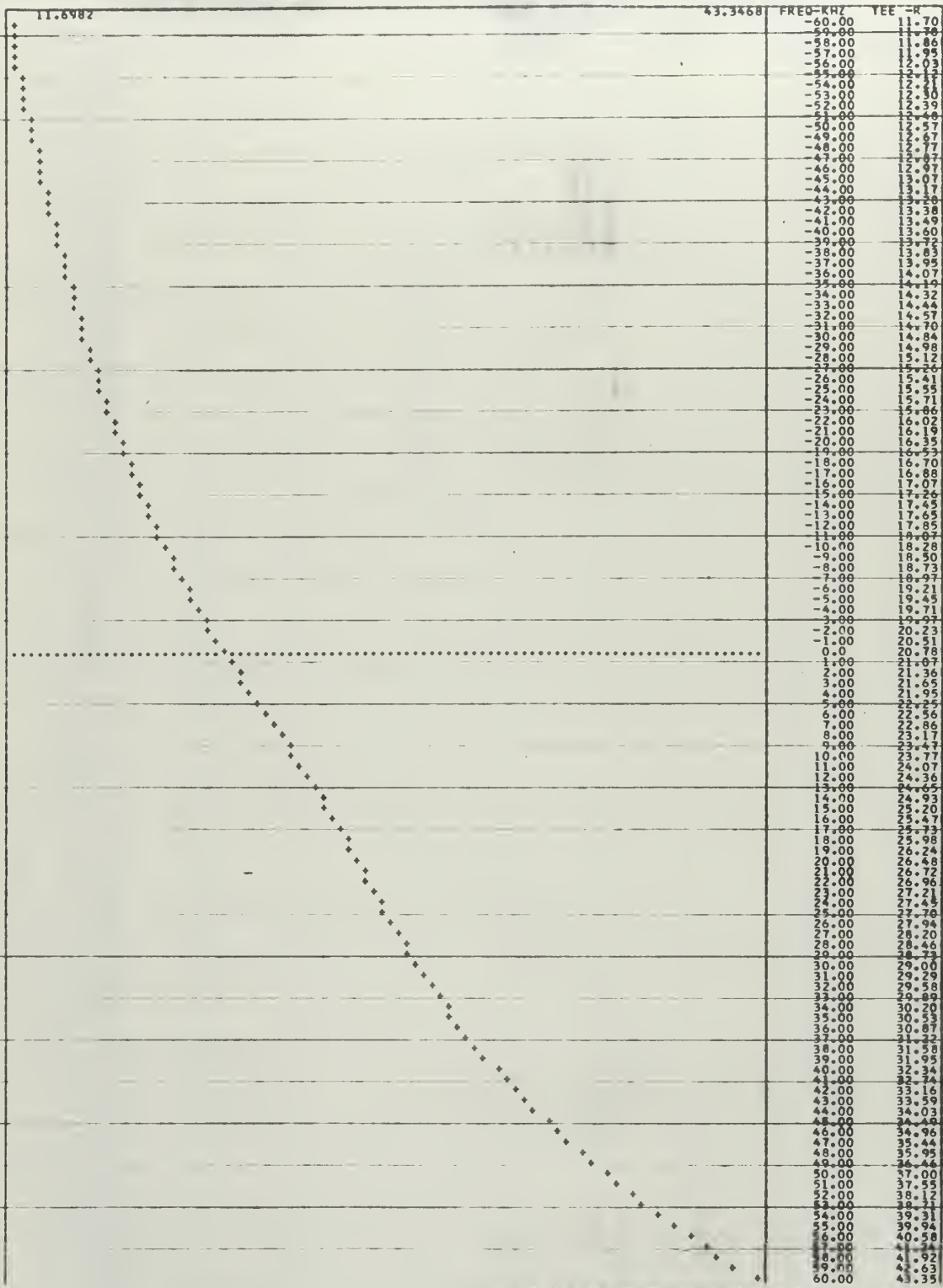


VARIATION IN COMPLEX HELIX IMPEDANCE VERSUS FREQUENCY

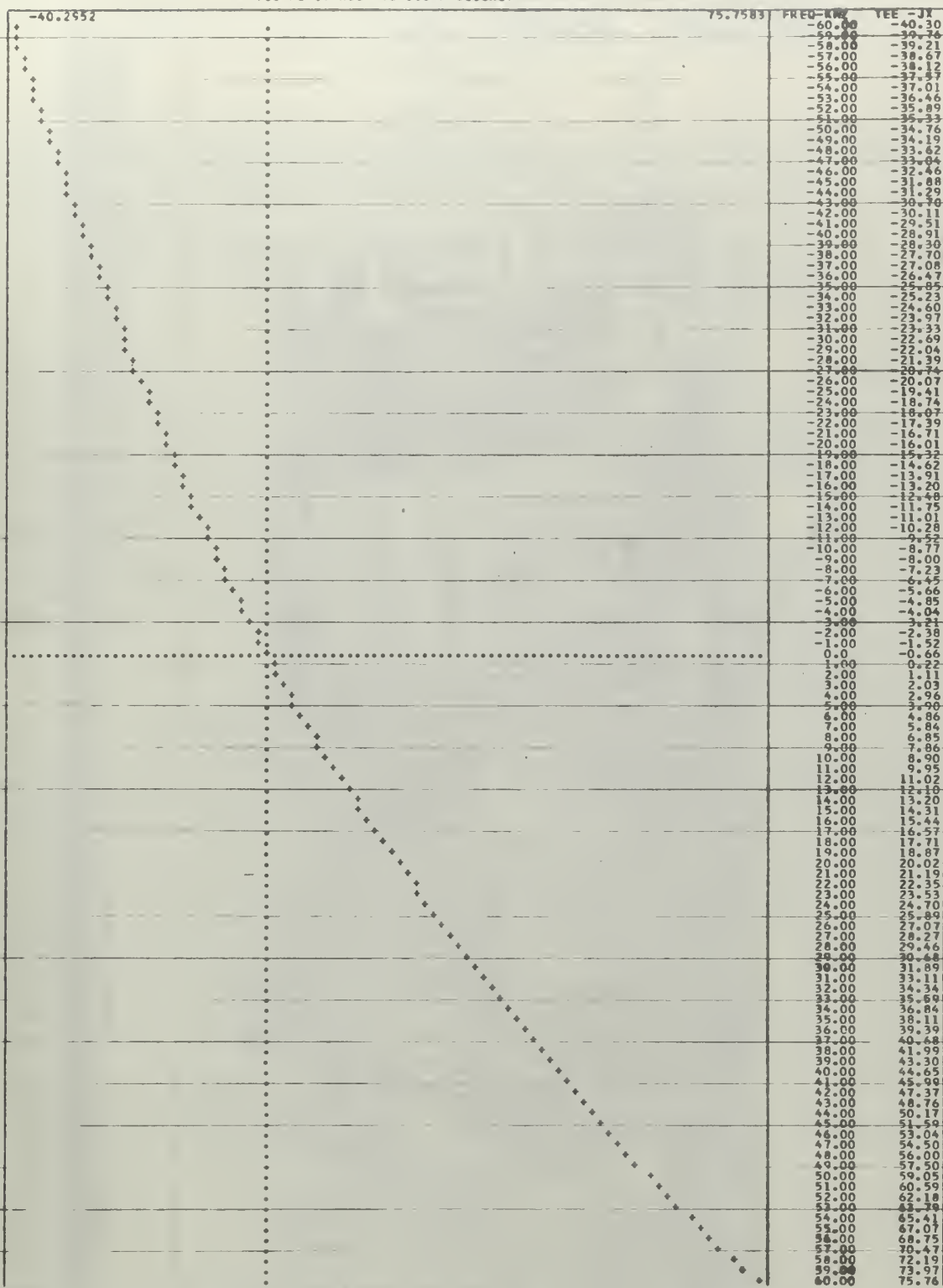


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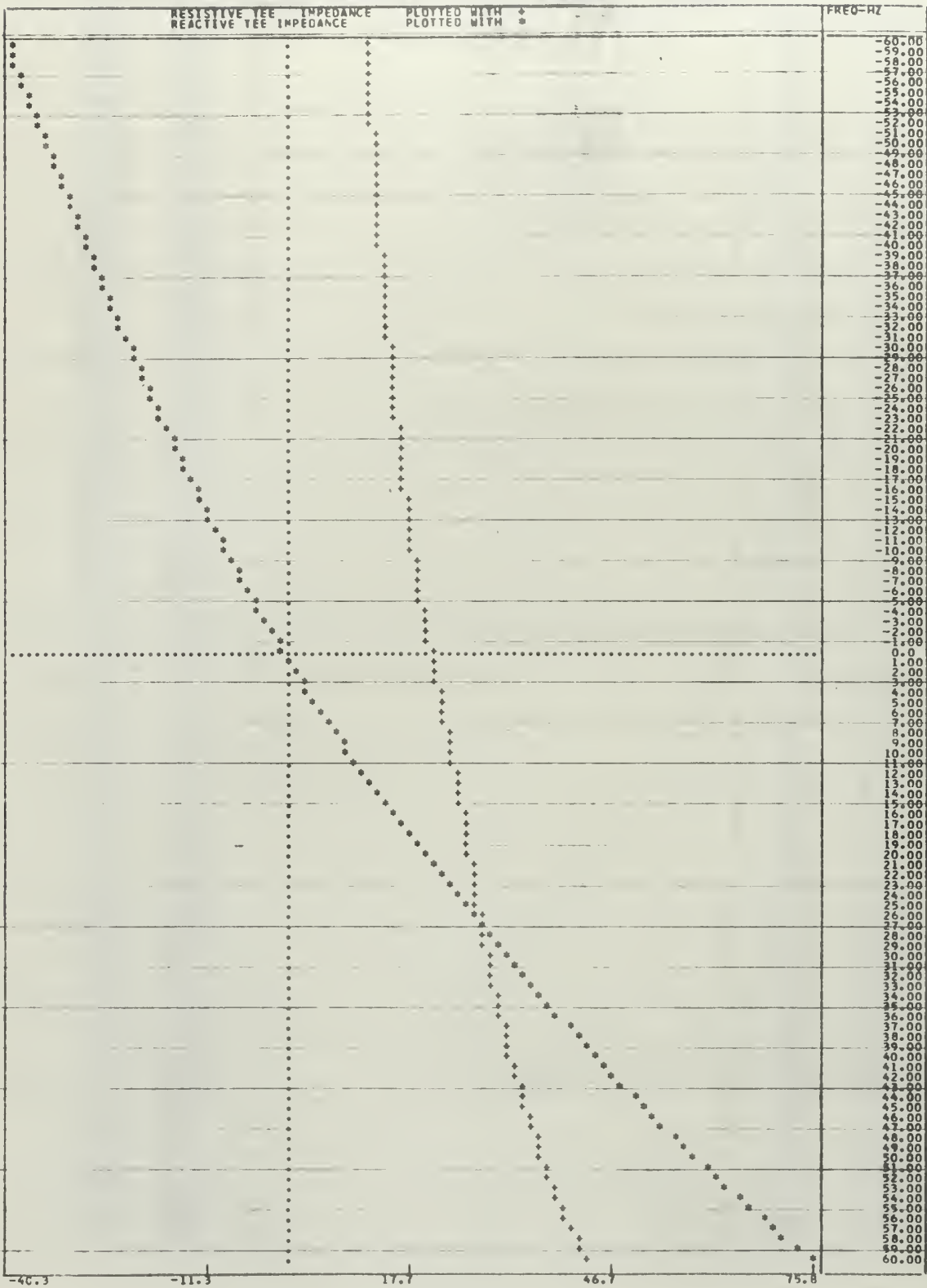
YEE RESISTANCE VERSUS FREQUENCY



YEE REACTANCE VERSUS FREQUENCY



VARIATION IN COMPLEX TEE IMPEDANCE VERSUS FREQUENCY



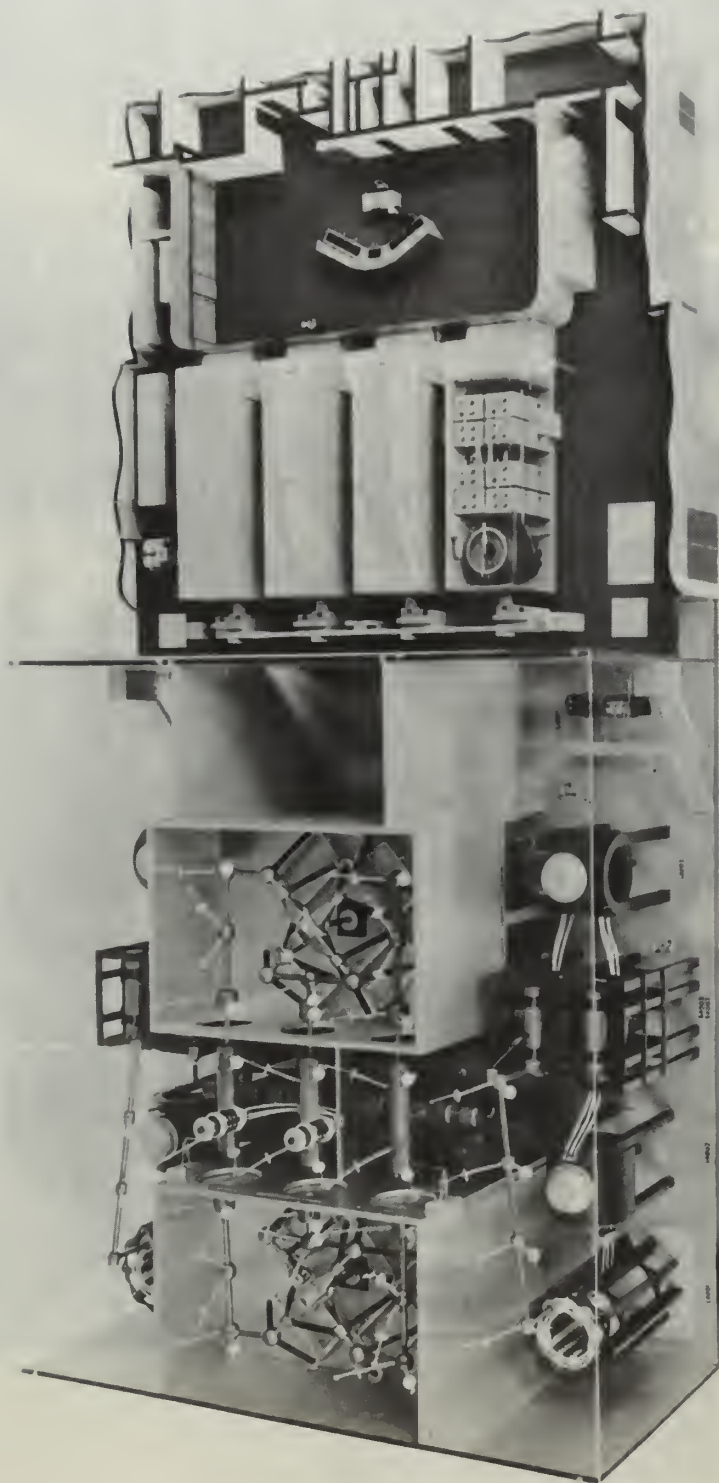


Figure 50

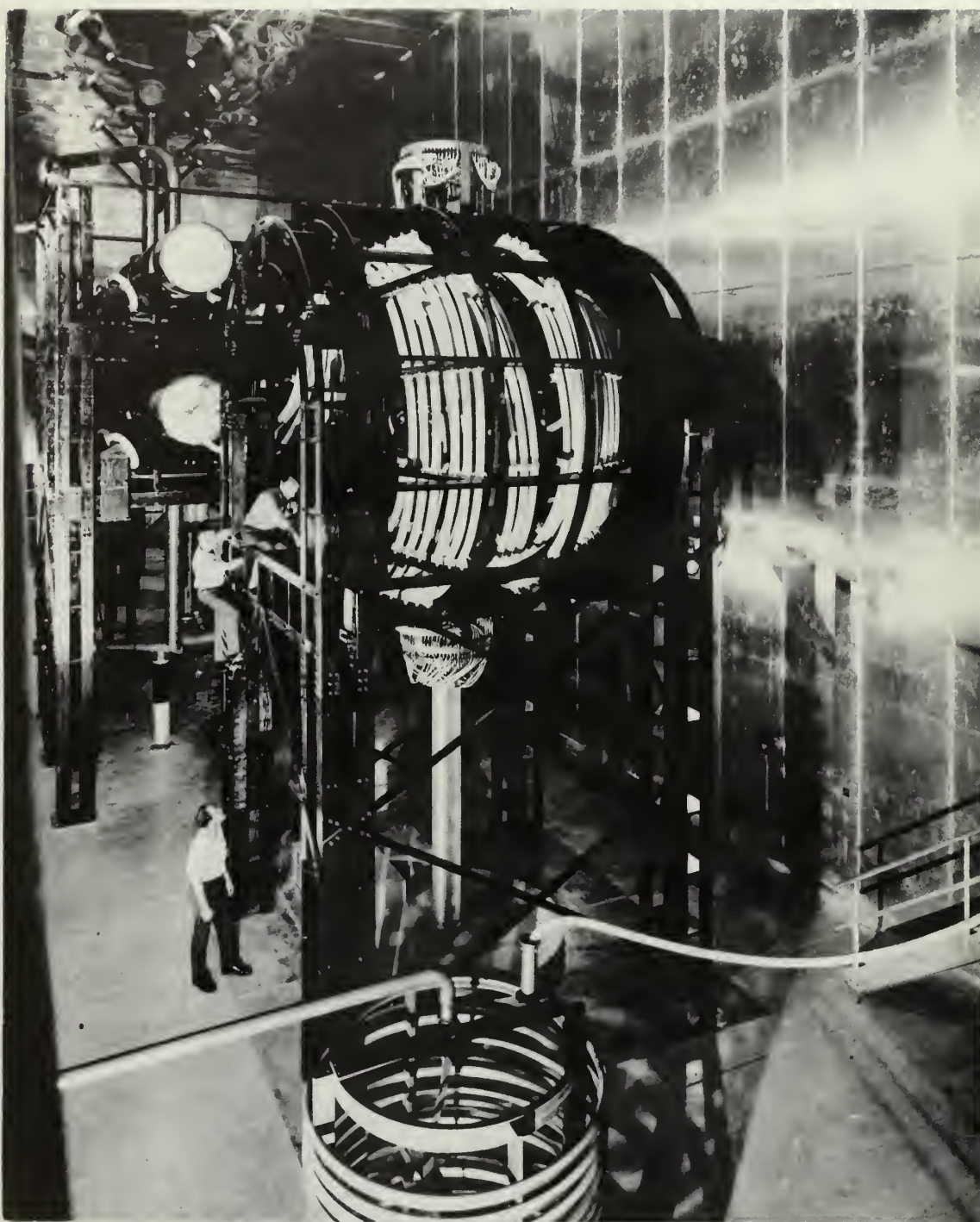


Figure 51

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<p>This thesis will be concerned with the antenna systems used for high power radio transmitters operating at Very Low Frequencies (10-30 kHz). General problems involved in antenna systems, from the viewpoint of their equivalent electrical circuits, will be discussed. The required matching networks will be covered and their relative performances indicated. A brief survey of signalling methods commonly used at VLF is included, and the relation between these methods and the aerial systems is discussed.</p> <p>A computer program (VLFANT) will be developed for a typical VLF aerial installation which may be used in the selection of component values for optimum operation. Written in FORTRAN IV, it is for use on a high-speed digital computer. Circuit parameter values may be changed at will, and the system response using different network arrangements easily determined. With this program as a design tool proposed systems may be completely evaluated and proposed changes to operational systems easily studied.</p>			

14	KEY WORDS	LINK A		LINK B		LINK C	
		ROLE	WT	ROLE	WT	ROLE	WT
	Very Low Frequency (VLF)						
	Antenna						
	Antenna Matching Networks						
	Computer Analysis of Antenna Matching Networks						

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An aid for the optimum design of antenna



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